INTEGRATED SHIPBOARD
MAIN PROPULSION CONTROL SYSTEM

REPORT OF NBTL RDT&E
PROJECT B-511-I
F013-06-06 TASK 4205
10 June 1963
by
J. W. BANHAM, JR.

NAVAL BOILER AND TURBINE LABORATORY
PHILADELPHIA NAVAL SHIPYARD
PHILADELPHIA 12, PENNA.

PLATE NO. 10917

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~~ABSTRACT~~ ship's control system

~~Development~~ of an integrated main propulsion control system with automatic propeller speed response to bridge order requires a thorough understanding of the dynamic response characteristics of the propulsion machinery. Because of the complex nature of the various interactions of the machinery components, this development ~~is best~~ was undertaken with the aid of an analog computer. This ~~report~~ presentation is concerned with the simulation of a DLG-6 type power plant, and the development of its automatic shaft speed control system.

The results of simulation studies indicated that the integrated system proposal is technically feasible, and that the system required to produce optimum response and stability is necessarily non-linear and complex. Development of the system was based on the properties of the "turbine-follower" machinery arrangement. Chart records comparing this plant with a similar plant, conventionally controlled, are presented as enclosures to the report.

SUMMARY PAGE

The Problem

Current long range goals established by Navy technical policy planners include as an ultimate objective the development and construction of a naval ship (or ships) capable of completely automatic control from a remote center, ideally the bridge. Development of such a system requires considerable analytical work prior to undertaking the actual design or hardware evaluation of the equipment involved. This project is concerned with Phase I of the long range program: The analog computer simulation of an integrated main propulsion control system as a tool for development of design criteria and specifications.

Findings

Remote automatic control of main propulsion shaft speed of destroyer type vessels appears to be within the confines of technical feasibility; automation system and component equipment required must necessarily be of a sophisticated and advanced design.

Recommendations

It is recommended that further development of integrated main propulsion control systems for destroyer types be based on the preliminary analytical findings as reported herein. It is further recommended that, in view of the favorable results of this feasibility study, development work to produce the necessary hardware for complete system automation be undertaken under this and related RDT&E Tasks.

ADMINISTRATIVE INFORMATION

The Laboratory was authorized by Bureau of Ships letter NP/4; Ser 651A-993 of 31 July 1961, to conduct studies of integrated main propulsion control systems by analytical and analog computer methods. The research and development project number assigned was F013-06-06, Task number 4205; the Laboratory project number was B-511. This is a final report of Phase I of a research and development project; Phase I is concerned with the research portion only.

REPORT OF INVESTIGATION

INTRODUCTION

This project is concerned with the development of the systems and components required for the complete automation of a shipboard main propulsion power plant and associated auxiliary machinery. Phase I of the project, the subject of this report, was a system design study conducted with the use of the Laboratory's electronic differential analyzer (analog computer); a program was developed which simulated the dynamic characteristics of a DLG-6 Class frigate and its propulsion machinery. Studies relating to this system are described in this report.

OBJECT

The objective of Phase I of this project was to develop in detail the philosophy, arrangement, specifications, requirements, and operating parameters of an integrated main propulsion control system suitable for fully automatic regulation of main propulsion shaft speed in response to the speed order originating at the bridge. This development work was to be performed through use of an analog computer. The alternate schemes of turbine-following and boiler-following plant arrangement were to be particularly investigated.

PROCEDURE

I. Statement of Basic Requirements. Prior to undertaking development of the computer program certain basic guidelines were adopted as desirable design objectives or as necessary constraints which might establish limitations on system arrangements subsequently proposed. These conditions may be summarized as follows:

a. The entire machinery complex is viewed as an integrated system subject to centralized command via a digital type computer or by conventional means. System control in response to command inputs will be delegated to decentralized computer-control systems located in compartments in the vicinity of the various machinery spaces. Provision will be made for complete local manual operation, remote manual operation, semi-automatic operation, non-integrated automatic operation (in which system response is in accordance with inputs originating at the sub-loop control stations), or fully integrated automatic operation (in which system response is to inputs originating at the computer command control center).

b. The plant must respond to all commands from standby to Full Power with all boilers in operation.

c. The plant must be capable of automatic start-up, automatic shutdown, operating cross-connected or split, and operating with any number of boilers and auxiliaries on the line within the limits imposed by available capacities.

d. The system must be protected by alarm systems, safety interlocks, program controlled routine, and emergency procedures.

e. The plant shall be designed to be turbine-following, i.e., the shaft speed order shall produce input commands to the boiler system and engine throttles shall respond automatically to total boiler output. When the loop is opened, the plant shall automatically revert to conventional boiler-following.

f. The control system shall maintain shaft speed within plus or minus one RPM of ordered value when under steady state conditions.

II. Statement of Specific Requirements Relating to this Study. In addition to the general requirements outlined above, specific procedures applicable to the computer simulation were adopted in order to limit the study to the capacity of the Laboratory's computer. These requirements were as follows:

a. The computer program will include only that portion of the control system responsible for the routine "on-line" operation of the plant in response to bridge orders. The supervisory digital system will not be included in the simulation.

b. The simulation will include one boiler, one ahead turbine, and one astern turbine. The program will be scaled such that the single boiler simulation will appear to the engines as two boilers operating in parallel and sharing load equally.

c. In programming the dynamic response of the vessel, the effects of propeller cavitation on power and thrust will be neglected as being beyond the scope and purpose of the simulation.

d. In programming machinery and controls, "state of the art" components and systems will be simulated wherever possible. This will reduce the extent of "hardware" development required in Phase II of the project.

e. In the programming of dynamic component characteristics, maximum use will be made of available experimental data on the theory that simulation of a linearized transfer function generally requires less computer equipment than the simulation of analytical functions.

f. Plant variables which are not a part of the closed loop plant response will not be included in the simulation.

III. Plant Component Selection. In order to formulate a complete mathematical description of the entire system, the performance characteristics of each element of the plant must be known. The simulation study will be based on a hypothetical combatant type vessel comprised of the following elements:

a. Hull: DLG-6 Class, having displacement of 4770 tons standard, 5600 tons full load.

b. Propeller: DLG-6 Class, having 14.52 feet pitch at 0.7 radius, and 216,666 lb. $ft.^2$ polar moment of inertia (referred to propeller shaft).

c. Main Boilers: Foster-Wheeler Corporation DLG-6 Class, having Full Power rating of 167,000 pounds of steam per hour at 950 F, 1200 psig.

d. Main Engines: DeLaval Steam Turbine Company DLG-6 Class, rated at 42,500 SHP at Full Power (300 propeller RPM) Ahead, and 6500 SHP at Full Power (160 propeller RPM) Astern, with steam pressures at throttle 1050 psig and 1150 psig, respectively. The equivalent ship speeds for these conditions were assumed to be 36 knots ahead, and 11 knots astern.

e. Boiler Combustion Controls: Generally equivalent to those in use aboard DD945 and DLG-9 Classes, with modifications as later described in this report.

f. Boiler Feedwater Controls: Instrument type three-element system identical to those in use aboard many naval ships.

g. Main Forced Draft Blowers: Generally equivalent to Carrier Corporation DLG-9 Class, with rated capacity 37,800 SCFM at 117 "H_2O and 7950 RPM.

IV. Plant Component Dynamic Analysis. The mathematical description of the performance of the steam power plant is the sum total of the mathematical description of the elements listed above. These descriptions were obtained both analytically and experimentally as follows:

a. Hull: Consideration of the dynamics of the overall loop in which shaft speed is the controlled variable revealed that shaft speed is a function of propeller torque, which in turn is a function of propeller thrust, which in turn is a function of ship's speed. Because of these interactions, the dynamic performance of the ship's hull influences the dynamic response of the ship's machinery, thus requiring a mathematical analysis of hull response. This response may be considered to be directionally dependent, requiring separate analyses for the ahead and astern underway conditions. Taken individually, these responses were computed as follows:

1. Ahead ship speed: The speed of the ship at any time, t, is the net integral value of the ship's acceleration. The acceleration of the ship may be obtained from the following expression.

(1) $$F = M_s \frac{dV_s}{dt}$$

Where: F = net force acting on the ship's hull along the fore and aft axis, lb.

M_s = total ship displacement, lb. sec^2/ft.

dV_s/dt = acceleration, ft/sec^2

Integrating equation (1):

(2) $$V_s = \frac{1}{M_s} \int F \, dt, \text{ where } V_s = \text{ship speed, ft/sec.}$$

The net force, F, is the algebraic sum of the propellor thrust and the hull drag (neglecting wind resistance). For purposes of the simulation, the drag force will be assumed to be proportional to the square of the ship's speed, V_s. Model tests and actual ship trials indicate that drag forces generally vary with approximately the 1.8 power of speed; this is considered to be sufficiently near to a square function to permit use of the square function in the simulation. Summing these forces to obtain F:

(3) $$F = F_t + F_d = F_t + C_d V_s^2$$

Where: F_t = thrust, lbs.

F_d = drag, lbs.

C_d = drag coefficient, lb sec^2/ft^2

The thrust force exerted on the hull by the propellor may be obtained from the energy equation:

(4) $$F_t = \frac{\rho A}{g} (V_s + V_w) V_w$$

Where: ρ = water density, lb/ft^3

A = effective propellor surface, ft^2

g = acceleration of gravity, ft/sec^2

V_w = velocity of water passing through the propellor referred to the horizon, ft/sec.

Now $V_w = {}_pN - V_s$, where p = propeller pitch, and N = propeller speed, RPM.

(5) $$\therefore \quad F_t = \frac{\rho A}{g} (V_s + {}_pN - V_s)({}_pN - V_s)$$

$$= \frac{\rho A}{g} ({}_pN - V_s)\ {}_pN$$

The constants in the above equations can now be computed from steady state design values. At Full Power Ahead:

V_s = 36 knots = 3640 ft/min

N = 300 RPM

P = 14.5 ft.

T_p = rated torque = 750,000 ft. lbs.

The propeller torque and thrust are related by the expression:

(6) $$F_t = \frac{T_p V_s}{2\pi N e}$$

Where: e is the propeller efficiency, $\dfrac{V_s}{V_s + \frac{1}{2}V_w}$

Now, $$\frac{V_s}{V_s + \frac{1}{2}V_w} = \frac{V_s}{V_s + \frac{1}{2}({}_pN - V_s)} = \frac{2V_s}{V_s + {}_pN} = e$$

(7) $$\therefore \quad F_t = \frac{T_p V_s}{2\pi N\left(\dfrac{2V_s}{V_s + {}_pN}\right)} = \frac{T_p\ (V_s + {}_pN)}{4\pi N} \quad \text{ft. lbs.}$$

Substituting of Full Power values in equation (7):

$$F_t = \frac{.75 \times 10^6 \times (3640 + 14.5 \times 300)}{4\pi \times 300} = 1.585 \times 10^6 \text{ ft. lbs.}$$

This quantity, the Full Power ahead propeller thrust, is equal and opposite to the Full Power ahead drag resistance when the ship is at a steady underway speed of 36 knots:

(8) $$F_d = -F_t = C_d V_s^2$$

(9) or $$C_d = -\frac{F_t}{V_s^2} = -\frac{1.585 \times 10^6}{(3640)^2} = -.120 \text{ lb min}^2/\text{ft}^2$$

Substituting F_t in equation (5):

$$1.585 \times 10^6 = \frac{\rho A}{g}(14.5 \times 300 - 3640)(14.5 \times 300)/3600$$

$$\therefore \frac{\rho A}{g} = \frac{1.585 \times 10^6 \times 3600}{(4350 - 3640)(4350)} = 1845 \text{ lb sec}^2/\text{ft}^2$$

Therefore, equation (5) may be completed thus:

$$F_t = \frac{1845}{3600}(14.5N - V_s) \times 14.5N \quad \text{lbs.}$$

$$= 7.43\,(N)(14.5N - V_s)$$

We can now rewrite Newton's law for the hull acceleration, with all constants evaluated, by substitution of equation (10) into (3), (9) into (3), and (3) into (2). Thus:

$$V_s = \frac{1}{M_s}\int \left[7.43(N)(14.5N - V_s) - .120 \times 3600(V_s)^2\right] dt \tag{11}$$

For a standard displacement of 4770 tons,

$$V_s = \int \left[1.51 \times 10^{-4} (N)(14.5N - V_s) - 8.75 \times 10^{-4}(V_s)^2\right] dt, \text{ ft/min} \tag{11a}$$

2. Astern ship speed: An analysis identical to that above may be written for the astern condition in which the following rated conditions apply:

V_s = −11 knots = −1120 ft/min

N = −160 RPM

P = 14.5 ft.

T_p = −215,000 ft. lbs.

The computed Full Power astern thrust from equation (7) was F_t = −368,000 lbs. The corresponding drag coefficient, C_d, from equation (9) was .293 lb. min^2/ft^2, indicating that astern drag forces are about 2-1/2 times as great as those ahead. Substitution of these values in the appropriate equations gives rise to the expression for astern ship speed:

$$V_s' = \int \left[1.51 \times 10^{-4} (N) (14.5N - V_s') - 21.4 \times 10^{-4}(V_s')^2\right] dt, \text{ft/min} \tag{12}$$

It is to be noted that the absolute value of shaft speed is used in equation (12) in order to permit the propeller thrust force to change sign whenever the velocity of water through the propeller, referred to the propeller, changes sign.

b. Main Propulsion Machinery

1. Propeller Torque: In order to develop an analytical expression for propeller speed, determination of the net torque in the propeller shaft is required. The retarding torque at the propeller can be reasonably assumed to vary with the square of the angular speed of the propeller shaft according to the relation:

$$T_p = KN^2 \tag{13}$$

To solve for K, where T_p is in ft. lbs. and N in RPM, substitute Full Power values, such that

$$750{,}000 = K\,(300)^2$$

$$\text{or} \qquad K = 8.33$$

This relation can be considered to apply equally to ahead and astern rotation, except that the value of K will be permitted to change sign when N changes sign, thus indicating a reversal of the direction of applied torque.

2. Machinery Torque (ahead turbine): The torque characteristics of the main turbines are a function of the steam flow into the turbine nozzles and the rotational speed of the turbine shaft. To obtain

an analytical expression for this torque, use was made of the manufacturer's technical manual for the DLG-6 main turbines. The torque-speed map obtained from the manual appears as Figure 1 of this report. This map indicates that, for constant steam flow, the torque developed in the turbine rotor varies linearly with the rotor speed. The general equation for any point on the map is therefore:

(14) $$T_t = mN + T_o$$

Where: T_t = rotor torque, percent of rated

M = slope of the torque-speed curve

N = propeller shaft speed, percent of rated

T_o = locked rotor torque, percent of rated

A plot of the values of T_o against steam flow, Q, indicate that the locked rotor torque varies directly with the steam flow. Hence:

(15) $$T_o = AQ, \text{ where } A = \text{constant}$$

A plot of the values of "m" vs. steam flow, Q, Figure 2, reveals that the slope of any constant steam flow curve is proportional to the steam flow it represents. Hence:

(16) $$M = BQ, \text{ where } B = \text{constant}$$

Substituting now in equation (14):

(17) $$T_t = AQ + BQN$$

The value of "A" equals the value of T_o with Full Power steam flow. From Figure 1 it is observed that A = 2.1. The value of "B" is equal to the slope of the "m" curve of Figure 2, -1.08 $\frac{\%T}{\%N}$. Equation (17) is therefore:

(18) $$T_t = 1.08Q(1.95 - N)$$

Equation (18) is written in dimensionless form. To obtain torque in ft. lbs., we can now substitute rated Full Power ahead conditions:

(19) $$T_t = 1.08 \times 750{,}000 \times \frac{Q}{100} \left(1.95 - \frac{N}{300}\right)$$

Where: T_t is in ft. lbs.

Q is in percent Full Power

N is in RPM

3. Machinery Torque (astern turbine): Available data descriptive of the performance of the astern turbine were found to be lacking. An approximation to the torque-speed map was constructed as shown in Figure 3 from experimental data taken from NBTL Report No. T-236. This construction assumed all torque curves to be parallel. The general equation of these curves is:

(20) $$T_t = AQ - BN$$

which, from the data of Figure 3, reduces to:

$$T_t = \left[\frac{.74Q}{100} - \frac{.15N}{300}\right] 750{,}000$$

4. Propeller speed: The general equation for propeller shaft speed may be written:

$$2\pi \frac{dN}{dt} = \frac{1}{I_p}(T_t - T_p) \tag{22}$$

Where: $\frac{dN}{dt}$ = shaft speed, rev/sec

I_p = polar moment of inertia, lb. ft. sec^2

Integrating equation (22),

$$N = \frac{1}{2\pi I_p}\int(T_t - T_p)\ dt \tag{23}$$

The polar moments of inertia of the turbines, couplings, reduction gears, shafts, and propellor for this class vessel total to 102,560 lb. ft. sec^2 referred to the propeller axis. Substitution in equation (23) produces:

$$N = \frac{60}{(2\pi)(102,560)}\int(T_t - T_p)\ dt = 9.30 \times 10^{-5}\int(T_t - T_p)\ dt \tag{24}$$

c. Main Boiler

1. Steam pressure: The construction of the boiler simulation was based on experimental data obtained at the Laboratory for the CVA-60 and DLG-6 Class main boilers, NBTL Projects B-406 and B-502-I. These projects were conducted to obtain open-loop response data and transfer functions for the various systems comprising the main boiler. In both of these projects the boiler steam drum pressure was found to be responsive to variations in steam flow, feedwater flow, and fuel rate. At the time,

this simulation was prepared, open-loop response tests of the DLG-6 boiler were not completed. Accordingly, transfer functions previously obtained from transient response tests of CVA-60 were employed to simulate DLG-6, with suitable adjustment of time constants. The transfer functions used for simulation of the steam pressure (in the steam drum) heat balance were as follows:

(25) $$P_{sat}/W_s = -\frac{.00954}{200s + 1}, \quad \frac{psi}{lbs/hr}$$

Where: P_{sat} = change in steam drum pressure, psi

W_s = steam output, lbs/hr

S = a differential operator

(26) $$P_{sat}/W_s = \frac{.147}{200s + 1}, \quad \frac{psi}{lbs/hr}$$

Where: W_s = fuel rate, lbs/hr

(27) and $$P_{sat}/W_w = -\frac{.0018}{200s + 1}, \quad \frac{psi}{lbs/hr}$$

Where: W_w = feedwater rate, lbs/hr

The superheater outlet steam pressure was obtained by assuming a superheater and piping pressure drop proportional to the square of the steam output rate, such that:

(28) $$P_o = P_{sat} - KW_s^2$$

Where: P_o = superheater outlet pressure, psig

For the DLG-6 boiler, this pressure drop is equal to 75 psi at the Full Power rating.

$$\therefore \; KW_s^2 = 75, \quad W_s = 167,000$$

and $$K = \frac{75}{(167,000)^2} = 26.9 \times 10^{-10} \;\; hr^2/lb\ in^2$$

Rewriting equation (28):

$$P_o = P_{sat} - 26.9 \times 10^{-10} (W_s)^2 \tag{29}$$

2. Boiler drum water level: As in the steam pressure simulation, the drum water level system was constructed from transfer functions obtained from transient response data of CVA-60 boiler. Again the constants were modified to produce results corresponding to those anticipated for the DLG-6 boiler. The boiler water level responds to three disturbances: steam flow, feedwater flow, and fuel rate. These responses were expressed mathematically by the following transfer functions:

$$\Delta L/W_s = 3.82 \times 10^{-5}\left(\frac{1}{10S + 1}\right) - 1.67 \times 10^{-6}\left(\frac{1}{S}\right), \quad \frac{in/sec}{lbs/hr} \tag{30}$$

Where: ΔL = change in water level, inches

W_s = steam rate, lbs/hr

S = a differential operator

$$\Delta L/W_w = 1.67 \times 10^{-6}\left(\frac{1}{S}\right), \quad \frac{in/sec}{lbs/hr} \tag{31}$$

Where: W_w = feedwater rate, lbs/hr

and

$$\Delta L/W_o = 1.73 \times 10^{-3}\left(\frac{1}{2S + 1}\right), \quad \frac{in/sec}{lbs/hr} \tag{32}$$

Where: W_o = fuel rate, lbs/hr

d. Main Forced Draft Blowers: The forced draft blowers were assumed to possess the characteristics of the Carrier Corporation blowers for DLG-6 Class. These blowers contain both static and dynamic non-linearities in their response characteristics. The steady state non-linearity appears in the air flow vs. air flow demand curve shown in Figure 4. This curve was generated in an arbitrary function generator for inclusion in the air flow loop. The dynamic non-linearities were disregarded, since their properties were unknown. The transfer function of the blowers was presumed to be a linear second order lag, having real time constants of nine seconds and 0.2 seconds. Test data obtained during subsequent frequency response tests of these blowers disclosed that the measured response could be closely modeled with a second order lag having real time constants of 6.4 and .88 seconds. In view of the fact that other forced draft blowers have been found to contain principal response time constants as large as 12 seconds, the transfer function used in this program is considered a valid simulation of a typical real forced draft blower. This transfer function was expressed as:

(33) $$W_a/e_i = \left[\frac{1}{1 + 9S}\right]\left[\frac{1}{1 + .2S}\right]$$

Where: W_a = air flow, percent rated

e_i = air flow demand, percent rated

S = the Laplace transform

The analytical expression for forced draft blower response is similar in form to that of equation (23), for the main turbine. For integrations with relatively low natural frequencies (as in this case), the response can be neatly approximated in closed loop simulations by lags of the equation (33) type.

e. Boiler Automatic Combustion Controls and Feedwater Regulator: The combustion controls as used in the plant simulation corresponded to the systems currently in use aboard many ships of several classes. Simulation runs were to be conducted with both turbine-following and boiler-following plant arrangements. The combustion controls were, therefore, modified as required to suit the needs of each concept. In the conventional boiler-following cycle, the steam pressure control loop was closed by a pressure feedback signal, and load indexed by a boiler steam output signal; in the turbine-following cycle the steam pressure loop was closed through the turbine nozzle valve regulator, and load indexed with the boiler fuel input signal. The diagrammatic arrangement of these systems is shown in Figure 5.

The three element feedwater control system was of the conventional Navy standard arrangement; a diagram of the system appears in Figure 6.

The gains and natural frequencies of the various control elements were established as equivalent to those used in actual operating systems.

f. Shaft Speed Control System: The final control system, selected as that which provides optimum performance of the closed loop under normal and emergency conditions, was the result of extensive trial and error computer work. It included a shaft speed feedback tachometer, an error detector amplifier, non-linear controller, and accessory logic circuits for shaft speed reversal, etc. For a detailed description of the system refer to the Results section of this report.

V. Development of Computer Program. A computer program, based on the analysis and systems described in Section IV, was prepared. The diagrammatic arrangement of this program is shown in Figure 7. In the following discussion the operational amplifiers will be referred to by number according to their designation indicated in Figure 7; the same is true for the attenuating potentiometers. For example, amplifier 23 and potentiometer 14 in the diagram will be designated A-23 and P-14, respectively, in the discussion. The various elements of the computer comprising the program were as follows: (Refer to Section IV and Figure 7)

1. The thrust force, equation (5) was solved by A-16, A-19, Multiplier UV-D2, and potentiometer P-21. The thrust, F_t, appears at the output of the multiplier, and was recorded on channel 6 of the oscillograph.

2. The drag force, equation (8), was solved by A-14, A-18, and Multiplier XY-D2. The drag, F_d, appears at the output of the multiplier.

3. The ship speed, equation (2), was solved by A-14, P-18, P-22, and P-23. The ship speed appears at the output of A-18, and was recorded on oscillograph channel 8.

4. Circuitry for developing the propeller torque from equation (13) included multiplier UV-D3, amplifier A-20, and potentiometers P-19, P-28, and P-29.

5. Machinery torque (ahead turbine) was produced from equation (19) using multiplier UV-D1, A-17, A-22, and A-27, with P-14 and P-17. Steam flow to the ahead turbine as a function of throttle position was developed by A-22, A-28, A-44, and FG-D2.

6. Machinery torque (astern turbine) was computed from equation (21) with A-27, A-42, and A-48, with P-37 and P-39.

7. Propeller speed was obtained from equation (24) with integrator A-13 and potentiometer P-13.

8. Boiler drum pressure response to changes in steam, feed, and fuel rates indicated by the transfer functions of equations (25), (26), and (27), was generated by A-31 and A-32, with P-31, P-32, P-33, and P-36.

9. Superheater outlet pressure was obtained by solving equation (29), with flow squared in multiplier XY-D1, and subtracting from drum pressure in A-33.

10. Boiler drum water level response to changes in steam, feed, and fuel rates indicated by the transfer functions of equations (30), (31), and (32), was generated by A-30, A-34, A-35, A-36, A-37, A-38, A-39, and A-40, with P-30, P-34, and P-35.

11. The forced draft blower response, including the static non-linearity of Figure 4 and the transfer function of equation (33), was developed with A-3, A-4, A-8, A-9, function generator FG-D1, and P-7, P-8, and P-10.

12. The boiler feedwater regulator was comprised of P-1, P-5, P-11, and A-1. This arrangement simulated the conventional three-element

control system with the frequency response of the valve and transmitters assumed to be infinite.

13. The two-element (steam flow and pressure) combustion control system was comprised of A-6 (master), A-7, A-12 (oil flow controller), A-2 (air flow controller), P-3, P-4, and P-9. Frequency response of valves and transmitters was assumed to be infinite.

14. Circuitry for the shaft speed control loop was developed during simulation trials; this loop will be discussed in further detail in the "Results" section of this report.

VI. <u>Scaling of Computer Program</u>. In the following analysis an asterisk appearing above a quantity will designate that it is a voltage. A bar above the quantity will denote that it is the maximum scaled value of a variable.

The following scale values apply to the computer program throughout:

1. W_s = 200,000 lbs/hr = 120% F.P. = $\overset{*}{60}$v
2. W_w = 200,000 lbs/hr = 120% F.P. = $\overset{*}{60}$v
3. W_o = 15,400 lbs/hr = 120% F.P. = $\overset{*}{60}$v
4. N = 300 RPM = $\overset{*}{90}$v
5. T = 750,000 ft.lbs. = $\overset{*}{50}$v
6. F = $1,585 \times 10^6$ lbs = $\overset{*}{40}$v
7. V = 3640 ft/min = 36 K = $\overset{*}{72}$v
8. P = 600 psi = $\overset{*}{100}$v
9. L = 8 inches = $\overset{*}{36}$v
10. Q = 100% F.P. = $\overset{*}{100}$v
11. e_i = control signal, % F.P., = $\overset{*}{50}$v @ 100%
12. W_a = combustion air flow, % F.P., = $\overset{*}{50}$v @ 100%

1. Consider first the ship's speed integrator, A-14. Equations (2) and (3) can now be combined to produce:

$$(34) \qquad V_s = \frac{1}{M_s} \int \left(F_t + c_d V_s^2 \right) dt$$

The first term of this equation can now be scaled as follows:

$$\frac{72\overset{*}{V_s}}{\overline{V}_s} = \frac{72}{\overline{V}_s} \times \frac{32.2 \times 60}{4770 \times 2000} \left[\frac{\overline{F}_t}{40}\right] \int \left[\frac{40\overset{*}{F}_t}{\overline{F}_t}\right] dt$$

$$\text{or} \qquad K_{18}G_{14} = \frac{72 \times 1.585 \times 10^6 \times 32.2 \times 60}{3640 \times 4770 \times 2000 \times 40} = .158$$

$$\text{Let } G_{14} = 0.2, \quad \therefore K_{18} = \frac{.158}{.2} = .790$$

The second term (when the ship is moving ahead in the water) is associated with the ahead drag coefficient computed in equation (9). Substituting in equation (34) and scaling:

$$\frac{72\overset{*}{V_s}}{\overline{V}_s} = \frac{72}{\overline{V}_s} \times \frac{32.2 \times 60}{4770 \times 2000} \times (-.120) \left[\frac{\overline{V}_s}{72}\right]^2 (100) \int \left[\left(\frac{72V_s}{\overline{V}_s}\right)^2 \left(\frac{1}{100}\right)\right] dt$$

$$\therefore K_{22}G_{14} = \frac{72 \times 32.2 \times 60 \times .12 \times 3640^2 \times 100}{3640 \times 4770 \times 2000 \times (72)^2} = 0.123$$

$$\text{Let } G_{14} = 1, \quad \therefore K_{22} = .123$$

The setting of potentiometer P-23 will be in the ratio of the drag coefficients, i.e.:

$$K_{23} = K_{22} \times \frac{C_d \text{ (astern)}}{C_d \text{ (ahead)}} = .123 \times \frac{.293}{.120} = .300$$

if G_{14} is again equal to unity.

2. Scaling of the thrust force, F_t, from equation (10), can be obtained by separating the components. The $p^N - V_s$ term developed by amplifier A-19 can be scaled as follows:

$$\frac{72(\overset{*}{p^N - V_s})}{\left(\overline{p^N - V_s}\right)} = \left[\frac{72}{\left(\overline{p^N - V_s}\right)}\right]\left[\frac{14.5\overline{N}}{72} - \frac{\overline{V_s}}{72}\right]\left(\frac{72(\overset{*}{14.5N})}{14.5\overline{N}} - \frac{72\overset{*}{V_s}}{\overline{V_s}}\right)$$

$$\therefore \quad K_N G_{19} = \frac{72 \times 14.5 \times 300}{3640 \times 72} = 1.195$$

$$\text{and} \quad K_{V_s} G_{19} = \frac{72 \times 3640}{3640 \times 72} = 1$$

In order to conserve on computer equipment, let us now select a scaling for A-19 such that no attenuation will be required at the multiplier UV-D2. This has the further advantage that the voltage input to the multiplier will remain reasonably high, thus preserving accuracy in the multiplier. This procedure is equivalent to assigning a new velocity scale factor to the $pN - V_s$ term. The equation for the multiplier now becomes:

$$\frac{40\overset{*}{F_t}}{\overline{F_t}} = 7.43\left[\frac{40}{\overline{\overline{F_t}}}\right]\left[\frac{\left(\overline{p^N - V_s}\right)}{\overset{*}{\overline{V}}}\right]\left[\frac{\overline{N}}{90}\right]\left[100\right]\left(\frac{\overset{*}{\overline{V}}\left(p^N - V_s\right)^*}{\left(\overline{p^N - V_s}\right)} \times \frac{90\overset{*}{N}}{\overline{N}} \times \frac{-1}{100}\right)$$

Substituting Full Power scaled values:

$$\overset{*}{40} = \frac{7.43 \times 40}{1.585 \times 10^6}\left[\frac{14.5 \times 300 - 3640}{\overset{*}{\overline{V}}}\right]\left[\frac{300}{90}\right]\left[100\right]\left(\frac{\overset{*}{\overline{V}} \times 90}{100}\right)$$

and, since $\frac{\overset{*}{V} \times 90}{100} = 40,$

$$\frac{7.43 \times 40}{1.585 \times 10^6} \left[\frac{14.5 \times 300 - 3640}{\overset{*}{V}}\right] \left[\frac{300}{90}\right] \left[100\right] = 1$$

$$\therefore \quad \overset{*}{V} = \frac{7.43 \times 40 \times 710 \times 300 \times 100}{1.585 \times 10^6 \times 90} = 44.5\text{v}$$

The scaling for ${}_pN\text{-}V_s$ is such that ${}_p\overline{N\text{-}V_s}$ = 710 ft/min = 44.5v.

Returning now to the previous equations developed for scaling amplifier A-19, and writing the equation for A-19 at rated conditions:

$$44.5 = K_nG_{19} \times 90 - K_{V_s}G_{19} \times 72$$

and

$$K_nG_{19} = 1.195 \times K_{V_s}G_{19}$$

Solving these equations simultaneously,

$$K_nG_{19} = 1.49$$

and

$$K_{V_s}G_{19} = 1.25$$

Let $G_{19} = 1.25$ for the V_s input to A-19; thus $K_{V_s} = 1$, and no potentiometer is required. Let $G_{19} = 2.5$ for the N input to A-19; thus

$$K_n = K_{21} = \frac{1.49}{2.5} = .598$$

3. Scaling of the torque developed by the main propulsion turbine is based on the expanded form of equation (19):

$$T_t = 809{,}000 \left[\frac{1.95Q}{100} - \frac{QN}{100 \times 300}\right]$$

Scaling the first term,

$$\frac{50\overset{*}{T}_t}{\overline{T}} = \frac{50}{\overline{T}} \times 809{,}000 \times \frac{\overline{Q}}{100} \times \frac{1.95}{100} \left[\frac{100\overset{*}{Q}}{\overline{Q}}\right]$$

$$\text{and } K_{14}G_{17} = \frac{50 \times 809{,}000 \times 1.95 \times 100}{750{,}000 \times 100 \times 100} = 1.05$$

Let $G_{17} = 5, \quad \therefore \quad K_{14} = .210$

Scaling the second term:

$$\frac{50\overset{*}{T}_t}{\bar{T}} = \frac{50}{\bar{T}} \times 809{,}000 \times \frac{\bar{Q}}{100} \times \frac{\bar{N}}{90} \times \frac{100}{100 \times 300}\left(-\frac{100\overset{*}{Q}}{\bar{Q}} \times \frac{90\overset{*}{N}}{\bar{N}} \times \frac{1}{100}\right)$$

$$\text{and } K_{17}G_{17} = \frac{50 \times 809{,}000 \times 100 \times 300 \times 100}{750{,}000 \times 100 \times 90 \times 100 \times 300} = .600$$

Let $G_{17} = 2.5, \quad \therefore \quad K_{17} = .240$

4. The torque developed by the astern turbine can be scaled in similar fashion from equation (21):

$$T_t = 750{,}000 \left[\frac{.74Q}{100} - \frac{.15N}{300}\right]$$

Scaling the first term:

$$\frac{50\overset{*}{T}_t}{\bar{T}} = \frac{50}{\bar{T}} \times 750{,}000 \times \frac{.74}{100} \times \frac{\bar{Q}}{100}\left(\frac{100\overset{*}{Q}}{\bar{Q}}\right)$$

$$\text{or } K_{37}G_{42} = \frac{50 \times 750{,}000 \times .74 \times 100}{750{,}000 \times 100 \times 100} = .370$$

Let $G_{42} = 1; \quad \therefore \quad K_{37} = .370$

Scaling the second term:

$$\frac{50\overset{*}{T}_t}{\bar{T}} = \frac{50}{\bar{T}} \times 750{,}000 \times \frac{.15}{300} \times \frac{\bar{N}}{90}\left(-\frac{90\overset{*}{N}}{\bar{N}}\right)$$

$$\text{or } K_{39}G_{42} = \frac{50 \times 750{,}000 \times .15 \times 300}{750{,}000 \times 300 \times 90} = .0833$$

Let $G_{42} = 0.1; \quad \therefore \quad K_{39} = .833$

5. The retarding torque afforded by the propeller, T_p, is scaled from equation (13):

$$T_p = 8.33\ N^2$$

$$\frac{50\overset{*}{T_p}}{\bar{T}} = \frac{50}{\bar{T}} \times 8.33 \times \left[\frac{\bar{N}}{90}\right]^2 \times 100 \left(\left[\frac{90N}{\bar{N}}\right]^{\overset{*}{2}} \left[\frac{1}{100}\right] \right)$$

$$= .617 \left(\left[\frac{90N}{\bar{N}}\right]^{\overset{*}{2}} \left[\frac{1}{100}\right] \right)$$

The factor .617 can be included in the scaling of the feedback potentiometer in the shaft speed integrator, A-13. This procedure will conserve equipment and maintain high input voltages to the multiplier UV-D3. Refer to section 6 below.

6. The shaft speed integrator, A-13, can now be scaled for integration rate. An absolute value circuit is required in order that the propeller torque may change sign together with the propeller speed. Propeller speed is given by equation (24):

$$N = 9.30 \times 10^{-5} \int (T_t - T_p)\ dt$$

Referring to section 5, this may be written in scaled form as follows:

$$\frac{90\overset{*}{N}}{\bar{N}} = \frac{90}{\bar{N}} \times 9.30 \times 10^{-5} \times \frac{\bar{T}}{50} \int \left[\frac{50\overset{*}{T_t}}{\bar{T}} - .617 \left(\left[\frac{90N}{\bar{N}}\right]^{\overset{*}{2}} \left[\frac{1}{100}\right] \right) \right] dt$$

The input torque coefficient is therefore

$$K_{13} = \frac{90 \times 9.30 \times 10^{-5} \times 750{,}000}{300 \times 50} = .419$$

And the feedback torque coefficient is

$$K_{28} = .617 \times .419 = .258$$

both with gain of amplifier A-13 equal to unity.

7. The steam drum pressure transfer functions are given by equations (25), (26), and (27). Scaling of these equations produces the following program data:

From equation (25)

$$\frac{\Delta P_{sat}}{W_s} = -\frac{.00954}{200\,S + 1}, \quad \frac{psi}{lbs/hr}$$

The transfer function may be written in differential form:

$$200 \frac{d}{dt}\left[\Delta P_{sat}\right] = -.00954\, W_s - \Delta P_{sat}$$

Transposing terms and integrating:

$$\Delta P_{sat} = \frac{-1}{200} \int (.00954\, W_s + \Delta P_{sat})\, dt$$

Integrator amplifier A-31 can be scaled for its steam flow and steam pressure (feedback) inputs. Scaling term by term:

$$\frac{100 \overset{*}{\Delta P}}{\overline{\Delta P}} = \frac{100}{\overline{\Delta P}} \times \frac{1}{200} \times .00954 \frac{\overline{W}_s}{60} \int -\left[\frac{60\, \overset{*}{W}_s}{\overline{W}_s}\right] dt$$

$$\text{or} \quad K_{31}G_{31} = \frac{100 \times .00954 \times 200{,}000}{600 \times 200 \times 60} = .0265$$

$$\text{Let } G_{31} = .1 ; \quad \therefore K_{31} = .265$$

The feedback term is:

$$\frac{100\overset{*}{\Delta P}}{\overline{\Delta P}} = \frac{100}{\overline{\Delta P}} \times \frac{1}{200} \times \frac{\overline{\Delta P}}{100} \int -\left[\frac{100\overset{*}{\Delta P}}{\overline{\Delta P}}\right] dt$$

$$\text{or} \quad K_{36}G_{31} = \frac{100}{600} \times \frac{1}{200} \times \frac{600}{100} = .005$$

Let $G_{31} = .1$; $K_{36} = .050$

If we now let amplifier A-36 receive the remainder of the heat balance terms given by the transfer functions of equations (26) and (27), the time constant for all responses is fixed at 200 seconds by the setting of feedback potentiometer P-36. This can be seen to be a proper procedure, since all three transfer functions are first order with time constants equal to 200 seconds. Considering now the effect of fuel flow on pressure as given by equation (26),

$$\frac{\Delta P_{sat}}{W_o} = \frac{.147}{200\ s + 1}$$

In a manner similar to the preceding section the transfer function can be written in integral form as:

$$\Delta P_{sat} = \frac{1}{200} \int (.147\ W_o - \Delta P_{sat})\ dt$$

Again scaling the first term:

$$\frac{100\overset{*}{\Delta P}}{\overline{\Delta P}} = \frac{100}{\overline{\Delta P}} \times \frac{1}{200} \times .147\ \frac{\overline{W}_o}{60} \int \left(\frac{60\overset{*}{W}_o}{\overline{W}_o}\right) dt$$

$$\text{or} \quad K_{32}G_{31} = \frac{100}{600} \times \frac{1}{200} \times .147 \times \frac{15,400}{60} = .0315$$

Let $G_{31} = .1$; $K_{32} = .315$

The effect of feedwater flow on steam drum pressure is given by equation (27):

$$\frac{\Delta P_{sat}}{W_w} = - \frac{.0018}{200\ s + 1}$$

or: $$\Delta P_{sat} = - \frac{1}{200} \int (.0018 W_w + \Delta P_{sat})\ dt$$

Scaling the first term:

$$\frac{100 \Delta \overset{*}{P}}{\overline{\Delta P}} = \frac{100}{\overline{\Delta P}} \times \frac{1}{200} \times .0018 \times \frac{\overline{W}_w}{60} \int \left[- \frac{60 \overset{*}{W}_w}{\overline{W}_w} \right] dt$$

$$\text{or} \quad K_{33} G_{31} = \frac{100 \times .0018 \times 200{,}000}{600 \times 200 \times 60} = .005$$

$$\text{Let } G_{31} = .1 \ ; \ K_{33} = .050$$

In order to program the above equations, it was necessary to provide an inverter amplifier, A-36, to obtain proper polarity for both heat balance input, and fuel oil controller feedback. This inverter was assigned a time constant of one second, as an estimate of the response time of the return pressure fuel oil control valve.

8. The superheater outlet pressure is obtained by subtracting the pressure drop through the superheater from the drum pressure as shown by equation (29):

$$P_o = P_{sat} - 26.9 \times 10^{-10} (W_s)^2$$

Steam flow rate was squared in multiplier XY-D1, and scaling of A-33 accomplished as follows:

$$\frac{100\overset{*}{P}_o}{\bar{P}_o} = \frac{100}{\bar{P}_o}\left[\frac{P_{sat}}{100} \times \left(\frac{100\overset{*}{P}_{sat}}{P_{sat}}\right) - 26.9 \times 10^{-10} \times \left[\frac{W_s}{60}\right]^2 (100) \left(\frac{60\overset{*}{W}_s}{W_s}\right)^2 \frac{1}{100}\right]$$

Scaling the second term:

$$G_{33} = \frac{100 \times 26.9 \times 10^{-10} \times 200{,}000^2 \times 100}{600 \times 60^2} = 0.5$$

For the first term all factors cancel, leaving

$$G_{33} = 1.0$$

9. The boiler drum water level is obtained from the transfer functions of equations (30), (31), and (32). The effect of changes in steam flow on water level is given by equation (30):

$$\frac{\Delta L}{W_s} = 3.82 \times 10^{-5}\left(\frac{1}{10\ s + 1}\right) - 1.67 \times 10^{-6}\left(\frac{1}{s}\right), \ \frac{\text{in/sec}}{\text{lbs/hr}}$$

This equation can be written in integral form as:

$$\Delta L = 0.1 \int (3.82 \times 10^{-5}\ W_s - \Delta L)\ dt - 1.67 \times 10^{-6} \int W_s\ dt$$

The first integral is obtained from amplifier A-40, and the second from A-34. These components are then summed at A-39. Scaling term by term:

$$\frac{36\overset{*}{\Delta L}}{\bar{\Delta L}} = \frac{36}{\bar{\bar{\Delta L}}} \times \frac{3.82 \times 10^{-6} \times \bar{W}_s}{60} \int \left(\frac{60\overset{*}{W}_s}{\bar{W}_s}\right) dt$$

or $$K_{34}G_{37}G_{40}G_{39} = \frac{36 \times 3.82 \times 10^{-6} \times 2 \times 10^5}{8 \times 60} = .0573$$

and, letting $G_{37} = .1$, $G_{40} = 10$, $G_{39} = 2.5$,

$$K_{34} = \frac{.0573}{.1 \times 1 \times 2.5} = .229$$

The feedback term of A-40 is scaled as follows:

$$\frac{36\overset{*}{\Delta L}}{\overline{\Delta L}} = -\frac{36}{\overline{\Delta L}} \times 0.1 \times \frac{\overline{\Delta L}}{36} \int \left(\frac{36\overset{*}{\Delta L}}{\overline{\Delta L}} \right) dt$$

hence: $G_{40} = .1 = \left(\frac{1}{R_f C_f} \right)_{A-40}$

With $C_f = 1$, $R_f = .1$; no feedback potentiometer is required.

The remaining integration term is computed by integrator A-34. Scaling this term:

$$\frac{36\overset{*}{\Delta L}}{\overline{\Delta L}} = \frac{36}{\overline{\Delta L}} \, 1.67 \times 10^{-6} \times \frac{\overline{W}_s}{60} \int \left(-\frac{60\overset{*}{W}_s}{\overline{W}_s} \right) dt$$

hence: $G_{34}G_{39} = \frac{36 \times 1.67 \times 10^{-6} \times 2 \times 10^{5}}{8 \times 60} = .025$

let $G_{39} = .25$, $\therefore G_{34} = 0.1 = \left(\frac{1}{R_i C_f} \right)_{A-34}$

If $C_f = 1$, $R_i = 10$; no feedback potentiometer is required.

The effect of water flow on water level is given by the transfer function equation (31). This function is complementary to the second integration term of equation (30). Scaling is therefore identical to that above, with the exception of the change of sign of the input variable.

Hence:

$$G_{34}G_{39} = 0.025$$

and since $G_{39} = .25$, $G_{34} = 0.1$

The input resistor is again found to be 10 megohms.

The effect of changes in fuel rate on boiler water level is expressed as the transfer function, equation (32):

$$\frac{\Delta L}{W_o} = 1.73 \times 10^{-3} \left(\frac{1}{2S + 1} \right) , \quad \frac{\text{inches/sec}}{\text{lbs/hr}}$$

Again writing in integral form:

$$\Delta L = \frac{1}{2} \int (1.73 \times 10^{-3} W_o - \Delta L) \, dt$$

Scaling term by term:

$$\frac{36\overset{*}{\Delta L}}{\overline{\Delta L}} = \frac{36}{\overline{\Delta L}} \times \frac{1}{2} \times 1.73 \times 10^{-3} \times \frac{\overline{W}_o}{60} \int \left(\frac{60\overset{*}{W}_o}{\overline{W}_o} \right) dt$$

or $K_{35}G_{36}G_{35}G_{39} = \frac{36 \times 1.73 \times 10^{-3} \times 15,400}{8 \times 2 \times 60} = 0.625$

Let $G_{36} = 1.0$, $G_{35} = 2.0$, $G_{39} = 2.5$

$\therefore \; K_{35} = \frac{0.625}{1 \times 2 \times 2.5} = .125$

The gain of amplifier A-35 was selected as 2.0 in order to permit use of a single feedback resistor to obtain the two second time constant. This arises from scaling the second term above:

$$\frac{36\overset{*}{\Delta L}}{\overline{\Delta L}} = \frac{1}{2} \times \frac{36}{\overline{\Delta L}} \int - \frac{\overline{\Delta L}}{36} \left(\frac{36\overset{*}{\Delta L}}{\overline{\Delta L}} \right) dt$$

or $G_{35} = \frac{1}{2} = \frac{1}{R_f C_f}$

Let $C_f = 1$; $\therefore R_f = 2$. This fixes A-35 gain = 2.

In order to make use of an existing water level indicator used as a readout display in conjunction with the simulation, the normal water level was selected as 50 volts. This was accomplished by adding a 20 volt suppression through potentiometer P-30, into amplifier A-39 with a gain of 2.5. This same 20 volt signal was also used as the set point input to the feedwater regulator error detector and amplifier, A-30, again through a gain of 2.5.

10. The steady state forced draft blower non-linearity depicted in Figure 4 was generated in FG-D1. The function generator was scaled such that the input and output voltages were equal at 120 percent of full power air flow to the boiler. The blower transfer function of equation (33) was then scaled by considering the transfer function as two series-connected first order lags and programming term by term.

Hence: $W_a = \frac{1}{9} \int (e_i - W_a)\, dt$

$$\therefore \quad \frac{60\overset{*}{W}_a}{\overline{W}_a} = \frac{60}{\overline{W}_a} \times \frac{1}{9} \int \left(\left[\frac{\overline{e}_i}{60} \right] \left(\frac{\overset{*}{60 e_i}}{\overline{e}_i} \right) - \left[\frac{\overline{W}_a}{60} \right] \left(\frac{\overset{*}{60 W_a}}{\overline{W}_a} \right) \right) dt$$

$$\therefore \quad K_7 G_4 = \frac{60}{120} \times \frac{1}{9} \times \frac{120}{60} = .111$$

Let $G_4 = 1$, $\therefore$ $K_7 = .111$

Likewise: $K_8 G_4 = \frac{60}{120} \times \frac{1}{9} \times \frac{120}{60} = .111$

and if $G_4 = 1$, $K_8 = .111$

For the high frequency component:

$$W_a = \frac{1}{.2} \int (e_i - W_a)\, dt$$

$$\therefore \quad \frac{60\overset{*}{W}_a}{\overline{W}_a} = \frac{60}{\overline{W}_a} \times \frac{1}{9} \int \left(\left[\frac{e_i}{60} \right] \left(\frac{\overset{*}{60 e_i}}{e_i} \right) - \left[\frac{\overline{W}_a}{60} \right] \left(\frac{\overset{*}{60 W_a}}{\overline{W}_a} \right) \right) dt$$

Therefore: $G_3 = \frac{60}{120} \times \frac{1}{.2} \times \frac{120}{60} = 5.0 = \frac{1}{C_f R_i}$

and for the feedback:

$$G_3 = \frac{60}{120} \times \frac{1}{.2} \times \frac{120}{60} = 5.0 = \frac{1}{C_f R_f}$$

If we let C_f of A-3 = 1 , R_i and R_f = .2

11. The boiler automatic combustion controls and feedwater regulator were programmed as the analog equivalent of existing Navy pneumatic systems found aboard DLG types. The system parameters were established as equivalent to those known to provide satisfactory stability in actual service. The construction of the computer program will be evident by comparison of the control system block diagrams, Figures 5 and 6, with the computer diagram, Figure 7. Scaling of the control system parameters was as follows:

a. Boiler Combustion Control Master.

This unit serves as a transmitting relay for loading the boiler sub-control loops with shaft speed controller output when operating in the turbine-follower mode. When in the boiler-follower mode it serves as the steam pressure controller, receiving steam flow and pressure input information and loading the sub-loops as required. Under this condition its transfer function is:

$$e_o = K W_s + K (P_s - P_o)$$

where e_o = output, % F.P.

W_s = steam flow, lbs/hr

P_s = designed steam pressure, psi

P_o = superheater outlet pressure, psi.

When in this mode, the proportional band of this device is 24 percent when the steam pressure impulses are scaled to 120% output for 600 psi pressure variations. The transfer function is thus:

$$e_o = .6 \times 10^{-3} W_s + \frac{1}{.24} \times \frac{120}{600} (P_s - P_o)$$

$$= .6 \times 10^{-3} W_s + .833 (P_s - P_o)$$

Scaling term by term:

$$\frac{60\overset{*}{e}_o}{\overline{e}_o} = \frac{60}{\overline{e}_o} \left[.6 \times 10^{-3} \times \frac{\overline{W}_s}{60} \times \left(\frac{60\overset{*}{W}_s}{\overline{W}_s} \right) + .833 \frac{\overline{P}}{100} \left(\frac{100(\overset{*}{P_s} - P_o)}{\overline{P}} \right) \right]$$

$\therefore \quad G_6 = \frac{60}{120} \times .6 \times 10^{-3} \times \frac{200,000}{60} = 1.0 =$ gain of master amplifier A-6 on steam flow input.

and $G_6 = \frac{60}{120} \times .833 \times \frac{600}{100} = 2.5 =$ gain of master amplifier A-6 on steam pressure input.

The master serves a third function, i.e., to limit the steam pressure to some value above the normal operating pressure, but below safety valve lifting pressure, when the system is operating in the turbine follower mode and the speed control loop is inadvertently opened. By the same token it can be made to maintain a low limit steam pressure when the engine throttles are closed. These features were not considered a necessary part of the simulation, and were not included in the boiler program.

b. Combustion Air Flow Controller.

This unit receives the demand from the boiler master and the combustion air flow transmitter and applies proportional plus reset control to the error to load the forced draft blower actuators. The transfer function is:

$$e_o = K_1 \; (e_i - W_a) + \frac{1}{K_2 S} \; (e_i - W_a)$$

The field settings for this controller are proportional band = 100%, and reset rate = 3.3 repeats per minute. Substituting in the transfer function:

$$e_o = (e_i - w_a) \; (1 + \frac{3.3}{60S})$$

Scaling term by term:

$$\frac{60\overset{*}{e_o}}{\bar{e}_o} = \frac{60}{\bar{e}_o} \times \left[\frac{\bar{e}_i}{60} \left(\frac{60\overset{*}{e_i}}{\bar{e}_i} \right) - \frac{\bar{W}_a}{60} \left(\frac{60\overset{*}{W_a}}{\bar{W}_a} \right) \right] \left[1 + .055/_S \right]$$

$$\text{or} \quad \frac{K_3 G_2}{K_4} = \frac{60}{120} \times \frac{120}{60} \times 1 = 1$$

$$\text{Likewise} \quad \frac{K_9}{K_4} G_2 = \frac{60}{120} \times \frac{120}{60} \times 1 = 1$$

$$\text{and} \quad K_4 G_2 = \frac{60}{120} \times \frac{120}{60} \times .055 = .055$$

$$\text{let} \quad G_2 = .1 \; ; \quad \therefore K_4 = .550$$

For K_3 and K_9 let $G_2 = 1.0$; $\therefore K_3 = K_9 = K_4 = .550$

It will be noted that these potentiometers are shown set at K = .350 when operating in the turbine-follower mode, as indicated in Figure 7. This reflects an increase in the reset rate to 5.2 repeats per minute, a gain which resulted directly from improved phase margin in the boiler controls when the steam pressure feedback loop was opened.

c. Fuel Oil Flow Controller.

This device receives an input demand from the boiler master or the combustion air flow transmitter, whichever of the two is lower, and a feedback signal from the fuel oil flow transmitter (or differential relay in the case of return-flow fuel oil burners). It provides proportional plus reset action on the resulting error signal and loads the fuel return control valve. The transfer function for this element is:

$$e_o = K_1(e_i W_o) + \frac{1}{K_2 s}(e_i - W_o)$$

where W_o is in percent of full power.

The field settings for this controller are proportional band = 40%, and reset rate = 24 repeats per minute. Substituting in the transfer function:

$$e_o = \frac{1}{.40}(e_i - W_o)\left(1 + \frac{.40 \times 24}{60s}\right)$$

Scaling term by term:

$$\frac{\overset{*}{60e_o}}{\bar{e}_o} = \frac{60}{\bar{e}_o} \times \frac{1}{.40} \times \left[\frac{\bar{e}_i}{60}\left(\frac{\overset{*}{60e_i}}{\bar{e}_i}\right) - \frac{\bar{W}_o}{60}\left(\frac{\overset{*}{60W_o}}{\bar{W}_o}\right)\right]\left[1 + \frac{.16}{s}\right]$$

$\therefore$ G_{12} (for air and master inputs) =

$$\frac{60}{120} \times \frac{1}{.40} \times \frac{120}{60} = 2.5$$

$$\therefore \quad \frac{R_f}{R_i} = 2.5$$

For the reset term:

$$G_{12} = \frac{60}{120} \times \frac{1}{.40} \times .16 \times \frac{120}{60} = .40$$

$$\text{and } G_{12} = \frac{1}{R_f C_f} = .40\ ; \quad \text{Let } C_f = 1$$

$$\therefore \quad R_f = \frac{1}{.40} = 2.5$$

$$\text{and } R_1 = \frac{2.5}{2.5} = 1.0$$

The limiter circuit employed in the simulation was designed to limit the output of amplifier A-12 (fuel oil demand) to the actual amount of air available to the boiler at any time as indicated by the output of A-10. This is a slight deviation from the actual system which limits the controller input rather than its output. In view of the fairly high reset corner frequency however, the error is very small, and the simulation is more economical.

d. Drum Water Level Controller.

The three element feedwater regulator system was simulated "in toto" in amplifier A-1, The transfer function of the system is:

$$W_w = \left[K_1 \;(W_s - W_w) + K_2 \Delta L\right]\left[1 + \frac{1}{K_3 s}\right]$$

The field settings of this control system are: proportional band of level controller = 60%, proportional band of ratio relay = 100%, and reset rate = 15 repeats per minute. The water level transmitter range is 24 inches. In the simulation, the regulator was "tuned" to provide optimum performance. The gain of the controller with respect to water level was established at 2.25 with P-1, equivalent to a proportional band in the actual pneumatic circuit of 42%. The gain on the steam and water flow input terms was 1.25, in lieu of the 1.0 gain of the pneumatic system. Reset time was maintained the same in the simulation. The feedwater control valve and main feed pump characteristics were not included in the simulation. The output of the controller was presumed to be equivalent to the feedwater flow.

12. Shaft Speed Control System programming was performed largely by trial and error. The system arrangement as depicted in Figure 7 was the final result of many simulation trials. These trials are discussed in the Results section of this report. Several features of the control system that were incorporated into the initial program were retained throughout. These features included:

a. Positive throttle stops to maintain the steam flow to the engines shut off when the bridge order is zero RPM.

b. Throttle stops to maintain steam flow only to turbine corresponding to direction of speed order signal.

c. Arbitrary function generator to produce variation in ahead turbine flow according to nozzle valve lifting mechanism for DLG-6 main turbines. The function generator used was FG-D2 on the diagram.

d. Steam pressure control system designed to maintain boiler pressure constant by using turbine throttles as pressure regulators.

e. Proportional plus reset modes in the speed control loop to produce steady state propeller shaft speed within $\pm$ 1 RPM of speed order.

f. Base boiler load in the form of a variable auxiliary load. This load was established by assuming that the total auxiliary steam demand varies linearly with forced draft blower steam demand. Potentiometer P-2 was used to introduce the auxiliary steam load to amplifier A-5, thus summing engine steam and auxiliary steam rates to produce boiler steam rate. The potentiometer coefficient is found by a simple ratio of designed values as follows:

$$\% \text{ aux. load} = \frac{\text{boiler load} - \text{turbine load}}{\text{boiler load}}$$

$$\therefore \ \% \text{ aux. load} = \left(\frac{2 \times 167{,}000 - 267{,}000}{2 \times 167{,}000}\right) \times 100 = 20\%$$

Scaling amplifier A-5:

$$\frac{60\overset{*}{W}_s}{\overline{W}_s} = \frac{60}{\overline{W}_s}\left[.20 \, \frac{\overline{W}_s}{60}\left(\frac{60\overset{*}{W}_s}{\overline{W}_s}\right) + .80 \, \frac{\overline{W}_s}{60}\left(\frac{60\overset{*}{W}_s}{\overline{W}_s}\right)\right]$$

and $K_2 = .20$, $K_6 = .80$, $G_5 = 1$

<u>RESULTS</u>:

The results contained in this report describe the dynamic response of the integrated ship under study with two basic engineering systems. The first of these is comparable to a conventional ship's machinery plant, in which steam is fed to the main turbines through manually operated throttle valves. The speed of the main propulsion shaft is controlled by the throttle operator. Boiler load is established by turbine steam demand and the required fuel rate to the boilers is maintained by automatic closed loop control of superheater outlet pressure.

The second system is a radical departure from this arrangement in that the shaft speed is regulated by an automatic control system. The output of this system maintains the firing rate to the ship's boilers, and the boiler pressure is controlled by automatic opening of the engine throttles. This scheme is referred to as the "turbine-follower" steam power plant.

Simulated maneuvering operations were conducted with both systems. A recording oscillograph was used to record the transient variation of all principal variables during maneuvering runs.

Manual Control: The first group of runs, conducted with shaft speed control in the manual mode, was designed to provide a basis for comparison with subsequent automatic control of shaft speed trials. During these runs the steam flow to the main turbines was the independent variable in the system. The "worst" condition was established by requiring that the ahead and astern throttle valves could not be opened simultaneously. This subjected the boiler to maximum range load changes, and the combustion and feedwater controls to severest duty. The results were considered to be typical of those expected for a destroyer type, operating with all boilers on the line and with conventional plant and control system arrangements. These results appear in Figures 8a through 13b. Boiler performance is illustrated in the "b" charts, that of the propulsion machinery in the "a" charts.

Figures 8 and 9 illustrate rapid maneuvers from standby to full power and the reverse. It will be noted in Figure 8b that steam pressure at the superheater outlet decreased to 1100 psi during the load increase; recovery after the maneuver required 1½ minutes. This variation is considered typical of the DLG-6 class boilers, based on observations made in the Laboratory and during ship trials. Boiler water level increase due to "swell" was just over two inches, a value somewhat less than normally expected; this reflects the increased control system sensitivity in the simulation. Response of fuel flow at the beginning of the maneuver is permitted by the opening of the combustion control dampers and the initial presence of excess air. Fuel rate is therefore limited to the response of the forced draft blowers. Blower speed was set to a minimum value of 1800 RPM; blower response to actuator input is thus delayed approximately five seconds. Acceleration of the propeller to full ahead speed required 21 seconds, that of the vessel itself, 30 seconds. The machinery transients are shown in Figure 8a.

The reverse condition, recorded in Figures 9a and 9b, discloses a water level "shrink" of five inches, a steam pressure increase of 55 psi, a propeller speed response of one minute, and a hull speed response of two and one-half minutes. These long term responses, in contrast to the acceleration times, reflect the "coast down" times of the machinery and the vessel due to their inertial properties. Faster response can of course be obtained by "applying the brakes" with the astern turbine.

Corresponding transients are recorded during maneuvers to and from the full astern condition in Figures 10 and 11. Figures 12 and 13 illustrate the ship stopping times when reversing the direction of propeller rotation. These maneuvers represent the "crash ahead" and "crash astern" trials when the engine throttles are not operated simultaneously. Figure 12a indicates that the propeller stopping time under these conditions is 23 seconds, the same time required to reach full astern steam flow. Stopping time of the vessel is 35 seconds, in contrast to the two and one-half minute response associated with removal of ahead power. Boiler performance shown in Figure 12b again illustrates a steam pressure deviation of 50 psi, and boiler water level variation from minus five to plus four inches.

Automatic Control: Numerous trials were conducted with various arrangements of automatic shaft speed control systems. Conventional controllers, using two-element proportional, proportional plus reset, rate action, and automatic gain control were all investigated. None of these concepts provided the type of response desired, together with steady state stability. The final arrangement, concluded to provide satisfactory performance, was a complex combination of these and other features. The control elements and modes successfully employed in the propulsion shaft speed control loop included the following:

a. Tachometer-transmitter, for developing a D.C. voltage output proportional to shaft speed. In the simulation a velocity servo-motor was driven at the angular speed appropriate to the computer speed integrator output. This speed was detected by a low range tachometer whose output was used to form the error signal.

b. Potentiometer-transmitter and isolation amplifier, for developing a D.C. voltage output proportional to the desired shaft speed (bridge order).

c. Error detector amplifier, and speed order polarity detector and amplifier.

d. Two element throttle control, actuated by boiler superheater outlet pressure and total fuel oil flow impulses. Sensitivity to both inputs is adjustable in order to eliminate proportional offset and optimize response to pressure deviations.

e. Throttle clamps, designed to select ahead or astern throttle response to steam pressure according to polarity of shaft speed order.

f. Absolute value computer, to produce increase in boiler input in response to order for increased shaft speed in either direction.

g. Automatic gain circuit, to vary the proportional response sensitivity as a function of the magnitude of the error signal.

h. Speed error integrator, to produce slow reset trimming to desired shaft speed at steady state.

i. Degenerative derivative feedback of shaft speed, to attenuate controller response as angular acceleration of shaft increases.

j. Summing relay, to combine all control modes. The output of this relay represents the demand for heat input to the main boilers.

The system composed of the equipment and functions listed above is illustrated diagrammatically in Figure 14. The computer program of this system appears in Figure 7. This scheme produced nearly ideal control, defined in this case as minimum deviation of shaft speed from the desired value, together with absence of overshoot in response to a large step change in speed order. It is believed to be capable of fully remote automatic control of engine room and boiler room under all steaming conditions including variations in number of burners, blowers, and boilers in operation, cross-connected or split-plant operation, maneuvering, docking and undocking, and emergency stops. Combined with a supervisory computer and additional servo-mechanisms and transducers, it is capable of total integration into a vessel designed for automatic start-up, automatic routine and casualty procedure control, automatic navigation, and automatic securing.

Scaling of the control system outlined above, was accomplished for the computer simulation, as follows:

a. The speed order potentiometer was provided with excitation voltages e_{ahd} and e_{ast} of -30 and +16 volts D.C., corresponding to 300 RPM ahead and 160 RPM astern, respectively.

b. The speed polarity detector amplifier, A-49, was provided with a gain of 50, and $\pm$ 50 volt diode limiters. The output of this amplifier actuated the throttle selector relay, RE-1, and the controller absolute valve and gain selector relay, RE-2. These relays will respond to a change in speed order equivalent to one RPM from the "all stop" positions.

c. The error detector amplifier, A-C, was provided with adjustable gain at the operating panel. It formed an error signal proportional to the difference between speed order and speed feedback. The feedback is represented as the output of P-15, although in the actual simulation a velocity servo-motor and tachometer were employed. Scaling of P-15 was based on the simple ratio of speed scaling for the controller to speed scaling for the machinery.

$$K_{15} = \frac{30\overset{*}{N_c}}{\overline{N}} \div \frac{90\ \overset{*}{N_m}}{\overline{N}} = .333$$

The controller was formed by the following elements, and arbitrarily scaled by trial and error for optimum response and stability:

Amplifiers A-45 and A-47 develop a difference signal between net propeller shaft torque and controller output. The net shaft torque is of course proportional to the time derivative of shaft speed as given by equation (22). In a real system, this variable must be obtained by differentiating the tachometer output with respect to time. Amplifier A-45 maintains a minimum fixed input into the AGC circuit (multiplier XY-D3). When the controller output becomes more negative than the output of A-45, the controller governs; the multiplier output is therefore $(Ge_s-D)(Ge_s)K$, where G = controller gain, e_s = speed error, D is shaft acceleration, and K is the total component gain. When the controller output is less than that of A-45, A-45 prevails, and the multiplier output becomes $2K\left[(Ge_s - D)^2 + 50\ (Ge_s - D)\right]$. The multiplier output is referred to as the conditioned error signal, e_c, and is seen to be a discontinuous function of time and error. It has the property of increasing rapidly at an increasing rate as speed error increases, then increasing at a much lower rate to prevent saturation of subsequent computing elements. The conditioned error signal was recorded in channel 3c of the oscillograph.

The conditioned error signal is next introduced to a conventional proportional plus integral controller. The controller was simulated with amplifiers A-46 (an inverter), A-41 (the integrator), and A-24 (the summer). Integration time was established with potentiometer P-40. It is to be noted that a large positive conditioned error signal, sufficient to tend to produce a negative summer amplifier output, will drive the combustion control master output to zero thus producing high gain negative feedback to the integrator amplifier, forcing it to reverse polarity. This arrangement blocks out the reset action temporarily when the direction of speed order is suddenly reversed. The resulting control action was found to prove highly successful in preventing overshoot of propeller speed during emergency crash ahead or crash astern maneuvers.

The turbine follower system must be equipped to prevent loss of steam pressure in the boiler when the shaft speed order is zero. This was accomplished by allowing a steam pressure error representing controlled pressure below set point to feed back to the combustion control master to maintain sufficient boiler input to control steam pressure. Reduction of load will also tend to drop steam pressure, but the throttle response is sufficiently high to be offset by the forward resistance of the limiting diode.

The system is best understood by examination of the maneuvering results under automatic control of shaft speed. Consider for example Figures 15a, 15b, and 15c. These recordings were obtained from a simulated crash astern from full power ahead maneuver. The speed order was suddenly changed from 300 RPM ahead to 160 RPM astern as indicated in Figures 15a and 15c. The speed error in Figure 15c, corresponds to the change in speed order, resulting in a step change in error from zero to 160 RPM. The conditioned error signal initially increases in the positive direction until the speed order changes sign. At this instant the speed error and conditioned speed error saturate at their negative limits, and the integrator resets to zero. The time response of the controller output now becomes a function of the integrator time constant and the machinery response (feedback). As the speed error signals converge to zero, the integrator and summer outputs stabilize at values corresponding to full astern without overshoot.

Dynamic response of the machinery is illustrated in Figure 15a. Response to the change in speed order is characterized by smooth transition of propeller speed; ahead throttle closing and astern throttle opening occur simultaneously. The ahead throttle is permitted to close at its own natural speed, in this case 12 seconds. The astern throttle opens to control steam pressure, thus the natural closing of the ahead throttle acts as a "booster" in opening the astern throttle. Total response of the propeller shaft was 35 seconds from full ahead to full astern RPM.

Corresponding change in ship's speed was 55 seconds. It is interesting to observe the torque and thrust curves obtained in this maneuver. These curves bear a remarkable resemblance to results obtained by H. F. Nordstrom in model tests conducted at the Swedish State Tank, reported in Transactions of the Society of Naval Architects and Marine Engineers, Vol. 58, 1950, pp 274-275.

Boiler transients were recorded in Figure 15b. It is to be noted that the total steam output of the boiler was subjected to a relatively minor load change. The fuel input, however, was sharply reduced as a result of the polarity change of the corrected error signal and the resulting integrator reset. Fuel rate subsequently increased in response to the controller output. This difference is in contrast to the expected results of a similar maneuver with conventional boiler following control, in which the steam and fuel flow load change characteristics are reversed. It is also significant that a change in steam pressure of only 20 psi is experienced, in contrast to the 50 psi associated with conventional closed loop combustion and steam pressure control.

The characteristics of the two types of steam plants, as outlined thus far, are more or less independent of the response of the main forced draft blowers. Let us now examine a situation in which the final steam rate is greater than the initial rate. In this situation the fuel rate response is limited by that of the air flow to the boilers. Such a condition is evident in the reverse maneuver, crash ahead from full power astern. This maneuver is illustrated in Figures 16a, 16b, and 16c.

Figure 16b illustrates the response of fuel, air, and steam flow. Under this condition all variables moved directly from the astern to the ahead condition without decrease. The forced draft blower underwent complete response in a period of 22 seconds, allowing steam flow to change in 40 seconds. The corresponding propeller speed change from -160 to +300 RPM required 30 seconds, and the ship speed 35 seconds. Again note that the rate of change of propeller speed is steep through 90 percent of its range, but no overshoot occurs. Figure 16c illustrates a different type of control response due to the discontinuities and non-linearities programmed into the control system design. In this case, the saturation level of the conditioned error signal is allowed to exceed its astern value, thus offsetting the effect of resetting the integrator. As a result, the controller output drops slightly while the astern throttle is closing, then rises sharply until the speed error signal begins to diminish. (Note that this does not occur until the speed is within 60 RPM of the set point.) Thus the system operates essentially as a high gain open loop until the controlled variable responds to within a relatively small error band of the desired value. It is important to remember that the magnitude of the shaft RPM error band within which the loop is closed will increase with increasing rate of change of shaft RPM. This feature precludes the possibility of overshoot.

Let us now consider maneuvering operations in which the astern throttle is not permitted to open. Recorded data for the response to a step change to the "stop" condition from full power ahead, without use of the astern turbine, is presented in Figures 17a, 17b, and 17c. Figure 17c again illustrates the reversal of the conditioned error signal, and the resetting of the integrator. In this case however, the controller (summer) remained at a small fixed output which subsequently decayed as the conditioned error signal diminished. The actual error diminished very slowly as a result of the natural "coast-down" velocity of the ship and the propeller shaft. Starting at an initial speed of 36 knots, the speed was still three knots after a period of about two and a half minutes. The propeller continues to turn despite the complete loss of turbine power, due to the forward motion of the ship and the resulting "windmilling" effect. The ahead steam flow and torque, as illustrated in Figure 17a, reached zero after only 20 seconds. Boiler parameters essentially correspond to conventional boiler follower type control. This occurs as a result of permitting the ahead throttle to close at its natural speed. Firing rate to the boiler is reduced both by the action of the speed control system and the high pressure limit control loop. The 50 psi deviation appears to be the normal deviation of pressure during rapid load reduction due to the heat inertia, or so-called "flywheel" effect of the boiler.

In contrast to these results, Figures 18a, 18b, and 18c, illustrate the response to a "Stop" order from the bridge when the astern throttle valve is permitted to respond to the control system. Figure 18c again shows the polarity reversal of the conditioned speed error signal. With the "stop" order maintaining the integrator in its reset condition, all system response is proportional to the conditioned speed error. This effect permits the astern turbine throttle to open for a brief period as indicated in Figure 18a, with a resulting "braking action" that stops the propellor in 20 seconds. Without "braking action" on the vessel as is the case in a crash astern maneuver, the ship speed curve decays on a long time basis. The effects of this maneuver on boiler performance, depicted in Figure 18b, were materially less stringent than those of a simple reduction of load as shown in Figure 17. The steam pressure deviation was only 25 psi, resulting from the relatively slower reduction of boiler load due to the steam consumption of the astern engine.

Having demonstrated the capability of the system to meet requirements for emergency stop or reversal, we now turn our attention to rapid speed increases from the standby condition, such as might be encountered in ASW operations. Figures 19 and 20 illustrate load increases to full ahead and full astern, starting from an engine stopped condition. Figure 19c indicates the usual reversal of polarity of conditioned speed error, and the immediate response of the integrator from a zero initial condition. The controller output exhibits a characteristic proportional plus integral transient response. This chart also provides a graphic demonstration of the relation between true error and conditioned error: note that while the two curves converge to zero simultaneously, the rate of reduction of conditioned error is always larger. This effect results from the combined effect of automatic gain control and degenerative rate feedback of propeller speed.

Maneuvering from standby to full astern, Figure 20, produces generally similar responses with the exception of the lower sensitivity of conditioned error to true error. Transient effects of boiler performance as illustrated in Figure 20b are smooth and continuous; water level excursion is small and steam flow rate of change is of a reasonable magnitude. This rate of change appears to be generally compatible with limitations imposed by temperature considerations in the astern turbine crossover.

The crash stop from full power astern operation is presented in Figure 21, and crash stop from 20 knots ahead in Figure 22. Moving the throttle speed order from the astern condition to the stop position causes reset of the integrator but does not actuate the polarity detector amplifier and relay to permit the ahead throttle to open; the propeller and ship speed therefore "coast-down" to the full stop condition. A change in order to one RPM ahead will release the ahead throttle control, permitting the main turbine to apply braking force to the shaft. In contrast, the stop order from 20 knots produces a small response in the astern throttle while the ahead throttle is closing; the astern throttle then slowly closes as the propeller shaft comes to rest. This transient appears in the charts of Figures 22a and 22c.

Having demonstrated the capability of the shaft speed control system to produce satisfactory response to emergency stop or emergency reversal propeller speed orders, our attention turns to the characteristics of normal underway maneuvering conditions in which the ship speed is varied routinely to meet navigational or other requirements. Maneuvering from standby to 20 knots, 20 knots to full power, and full power to 20 knots is shown in Figures 23, 24, and 25, respectively. Simulated conditions of getting underway, consisting of a series of typical load and speed changes, is presented in Figure 26. Studies of these chart records indicate that underway performance of the vessel can meet all maneuverability requirements for this class, with the turbine follower type plant arrangement and the single lever speed order transmitter at the bridge.

CONCLUSIONS

Results of this project, described in the previous section of this report and illustrated graphically in the enclosures at the end of the report, are the basis for the following conclusions:

1. The design of an automatic shaft speed control system for main propulsion machinery of destroyer type vessels appears both practical and technically feasible.

2. The use of the turbine-follower steam plant arrangement for destroyer type vessels appears to be practical. This conclusion is recognized to be at odds with the findings of earlier investigators, but it is suggested that the satisfactory application of this principle is contingent on the development of a suitable control system and on the requirements for excellent transient response of the main forced draft blowers.

3. The turbine-follower system numbers several distinct advantages in comparison with the conventional arrangement: boiler steam pressure is maintained essentially constant, steam flow to the machinery can not exceed the total capability of the steam generating system at any time, boiler water level excursions are minimized, steam temperature excursions are minimized, and requirements for operating personnel are reduced.

4. The shaft speed control system should include automatic gain and degenerative rate feedback conditioning of the shaft speed error signal as previously outlined in this report. Systems that are more

straightforward and less complex are desirable from an economic and aesthetic standpoint; but are not considered likely to produce desired performance in wide range transients.

5. Limiting or logic circuitry must be included in the analog control system to perform the following functions:

a. Protection against high steam pressure.

b. Protection against low steam pressure.

c. Provide assurance that throttles are tightly closed and unaffected by spurious signals when the speed order is zero RPM.

d. Limit action of the speed error integrator when the bridge orders more speed than can be attained with any particular combination of boilers or burners in use. This function can readily be accomplished by automatically placing the integrator in "hold" when any one boiler master exceeds its rated output.

e. Light-off and secure fuel oil burners and air registers in response to changes in demand. This requirement stems from insufficient turn-down of currently available fuel burning systems to permit standby operation with all boilers in service.

f. Distinguish between "split-plant" and "cross-connected" modes of plant operation and exercise appropriate control action. This requirement was not simulated in the computer study in view of the fact that only one plant was programmed in the simulation. The simplest arrangement to meet this requirement is to permit the system to revert to closed loop pressure control boiler-following, with throttles directly positioned according to speed controller output.

g. Detect and initiate corrective action in response to "off-normal" plant variables. These functions can be programmed into supervisory digital equipment and combined with an annunciator or data-logging system if desired.

6. In order to capitalize on the capabilities of the proposed control system to reduce operating personnel, all sub-loops should be automated, and all systems designed and equipped for remote or automatic start-up and shut-down, as well as routine additional operation not specifically associated with continuous "on-line" control. These features again can be incorporated into a digital system.

7. The engine throttle servo-motors should be designed for velocity-limiting appropriate to the maximum allowable transient disturbance rate for two boilers. This rate time should be somewhat faster than the natural response time of the boilers.

8. The combustion and feedwater control sub-loops should be of the conventional type as illustrated in Figures 5 and 6. The fuel rate and steam pressure signals originating in the combustion control system

should be employed in the throttle position control servo loops as illustrated in Figure 14.

9. All computing, transmitting, and control components and systems should be designed to operate on solid-state electronic principles and techniques. Control drives and servo-mechanisms should be electrically powered. This requirement exceeds present day state-of-art technology but is expected to be within the realm of practicality in the near future. Development of such devices is presently in progress at the Laboratory under RDT&E Task 4185 of this Subproject.

RECOMMENDATIONS

It is recommended that:

a. Steam plant automation, with single lever bridge control of shaft speed order, for destroyer type vessels, be accepted as within the scope of technical feasibility, and that further developmental and design studies toward the realization of this objective be undertaken.

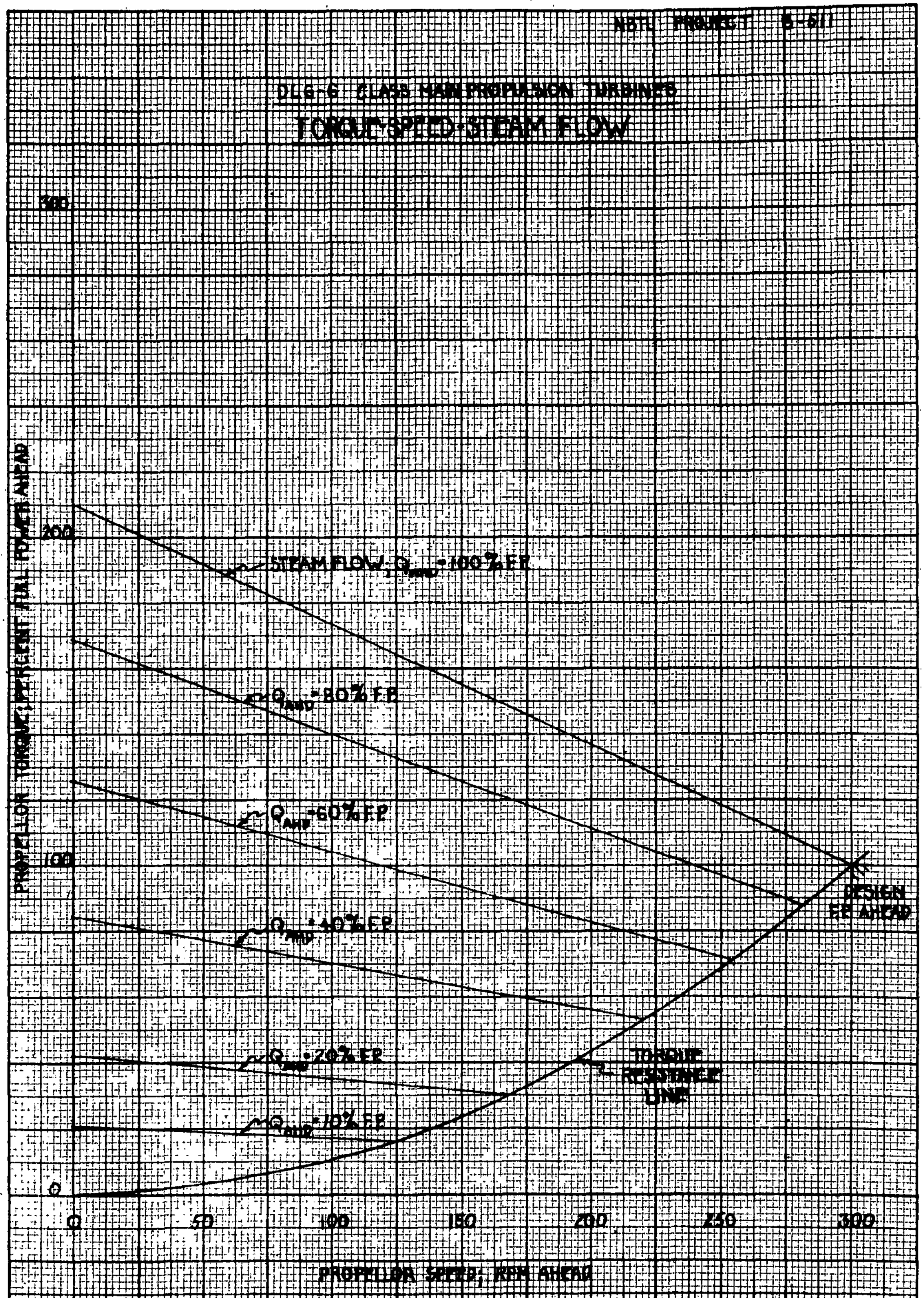
b. Initial control system designs for a naval power plant constructed for an automated ship be based upon the design proposals and stipulations detailed in this report.

c. Further investigative and developmental effort be expended to insure the availability of all necessary "hardware" for use in an automated shipboard steam power plant.

d. Additional computer studies of control subloops for auxiliary machinery and systems should be conducted.

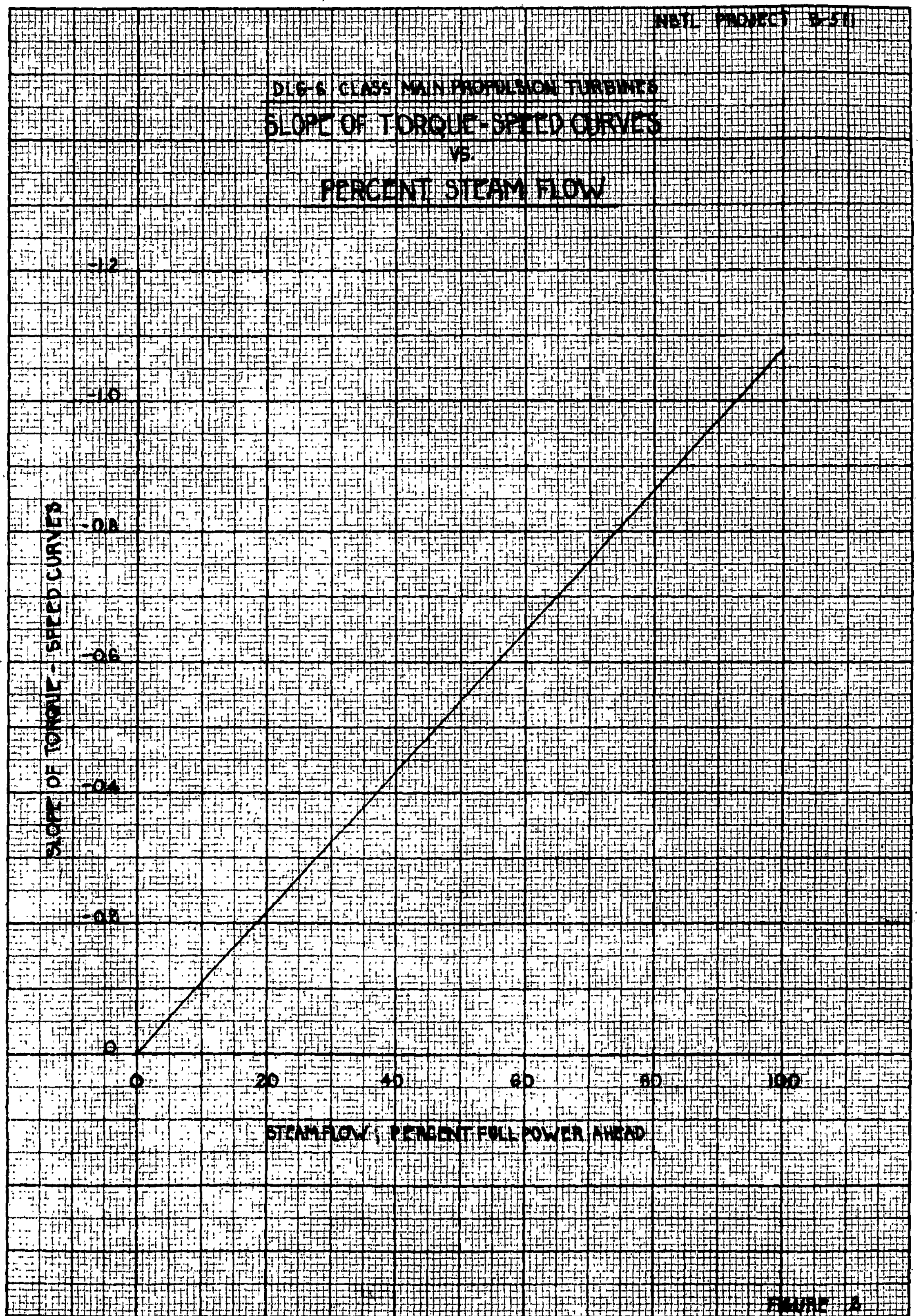
e. Suitable primary element transducers for use within the solid state electronic automated system should be specified, tested, and/or developed.

f. Design of the automated integrated vessel be coordinated between designers responsible for the various computing systems required for all of the functions of the ship. It is suggested that the digital computers visualized as the supervisory systems for engineering plant start-up, shut-down, and emergency procedures be integrated with a single computer responsible for navigational, missile control, fire control, combat information computation, and similar or related functions.



NBTL PROJECT B-611
DLG-6 CLASS MAIN PROPULSION TURBINES
TORQUE-SPEED-STEAM FLOW
PROPELLOR TORQUE; PERCENT FULL POWER AHEAD
300
200
100
0
STEAM FLOW, Q AHD = 100% F.P.
Q AHD = 80% F.P.
Q AHD = 60% F.P.
Q AHD = 40% F.P.
Q AHD = 20% F.P.
Q AHD = 10% F.P.
DESIGN F.P. AHEAD
TORQUE RESISTANCE LINE
0
50
100
150
200
250
300
PROPELLOR SPEED; RPM AHEAD

FIGURE 1


NBTL PROJECT B-511
DLG-6 CLASS MAIN PROPULSION TURBINES
SLOPE OF TORQUE-SPEED CURVES
VS.
PERCENT STEAM FLOW
SLOPE OF TORQUE - SPEED CURVES
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0
0
20
40
60
80
100
STEAMFLOW ; PERCENT FULL POWER AHEAD
FIGURE

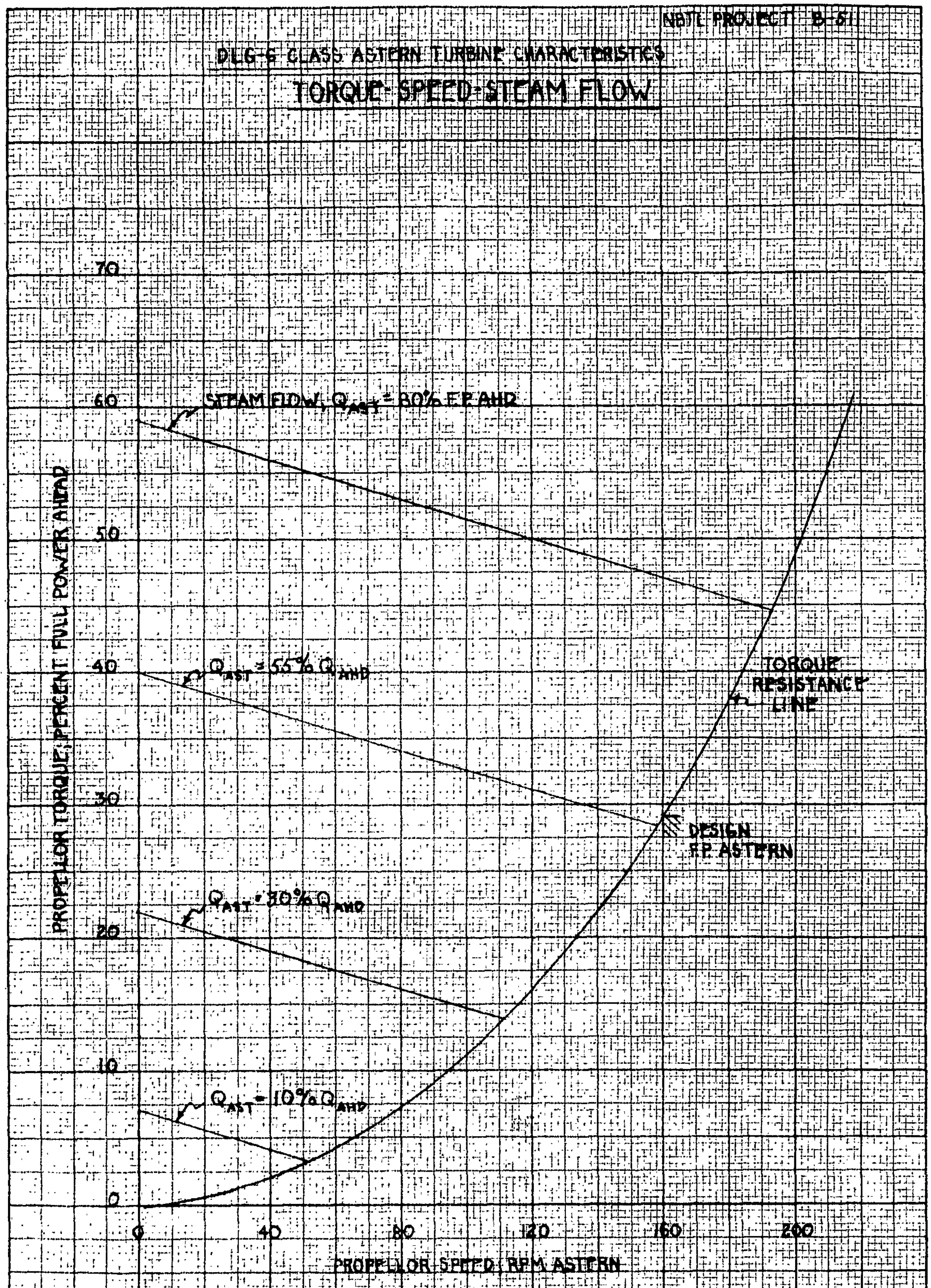
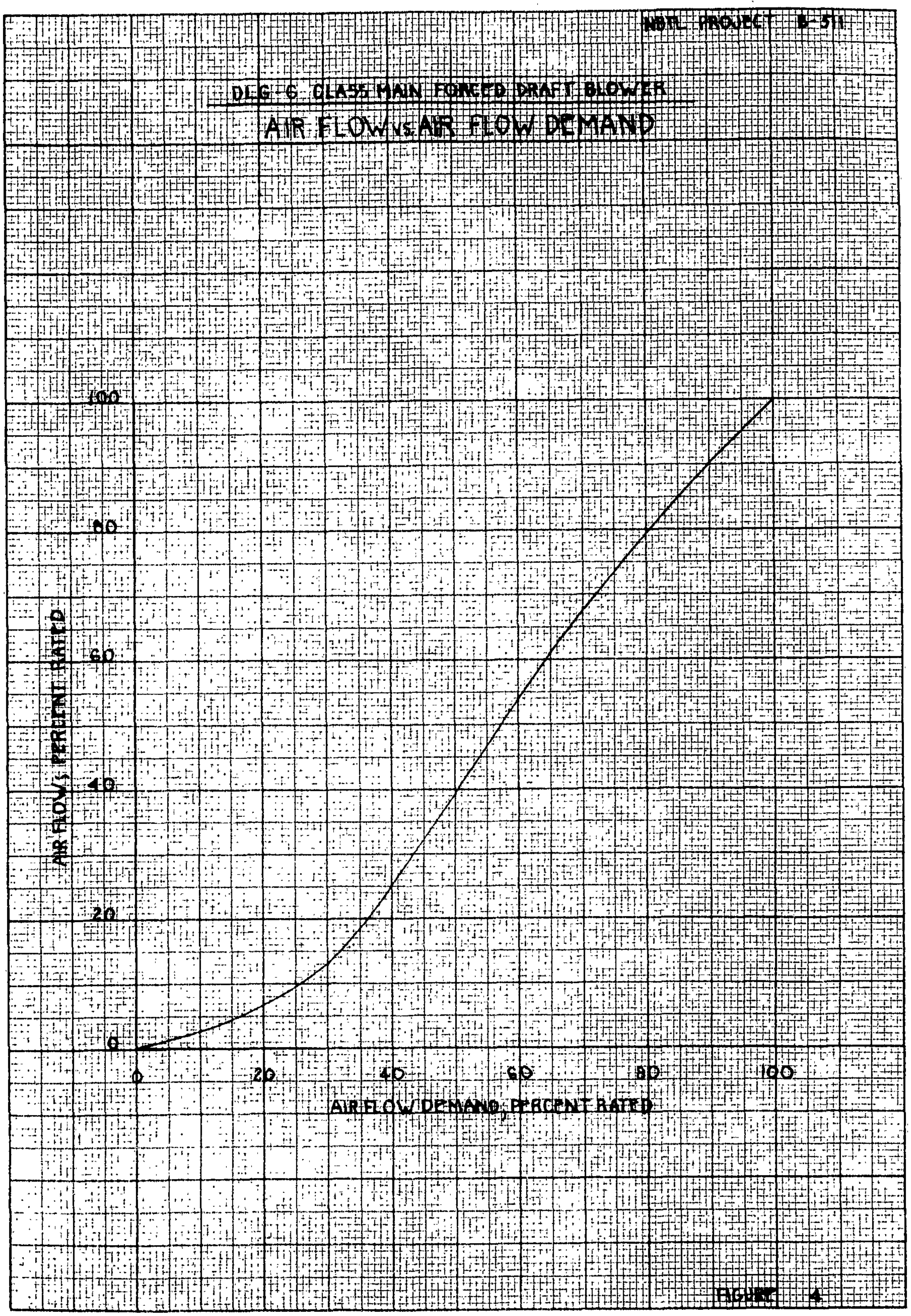
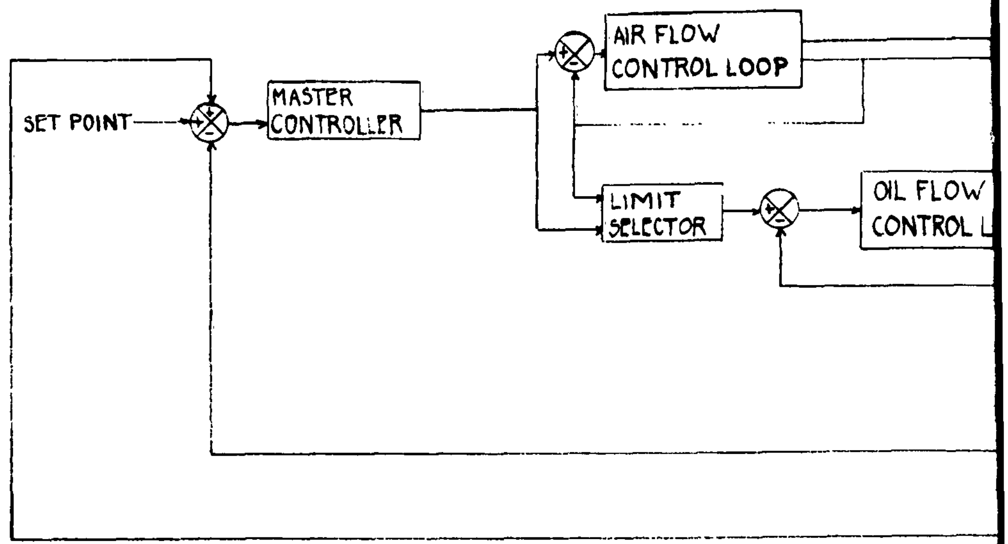

NBTL PROJECT B-51
DLG-6 CLASS ASTERN TURBINE CHARACTERISTICS
TORQUE-SPEED-STEAM FLOW
STEAM FLOW, Q_{AST} = 80% F.P. AHD
Q_{AST} = 55% Q_{AHD}
Q_{AST} = 30% Q_{AHD}
Q_{AST} = 10% Q_{AHD}
TORQUE RESISTANCE LINE
DESIGN F.P. ASTERN
PROPELLOR TORQUE; PERCENT FULL POWER AHEAD
PROPELLOR SPEED; RPM ASTERN
0
10
20
30
40
50
60
70
0
40
80
120
160
200

FIGURE 3

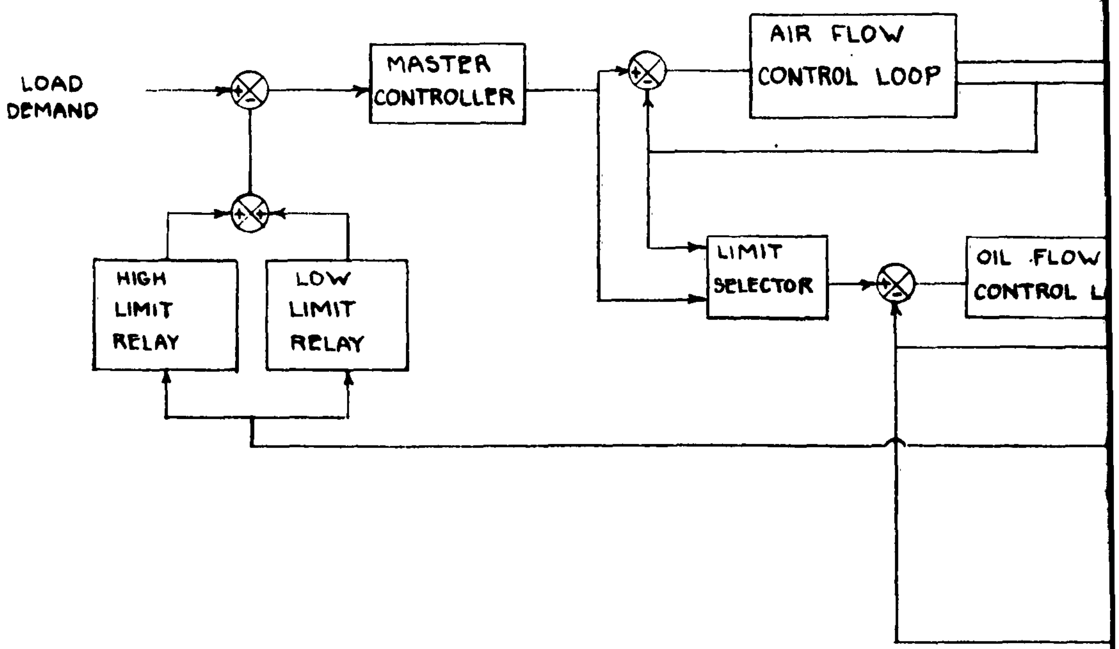


NBTL PROJECT B-511
DLG-6 CLASS MAIN FORCED DRAFT BLOWER
AIR FLOW vs. AIR FLOW DEMAND
100
80
60
40
20
0
AIR FLOW, PERCENT RATED
0
20
40
60
80
100
AIR FLOW DEMAND, PERCENT RATED

FIGURE 4

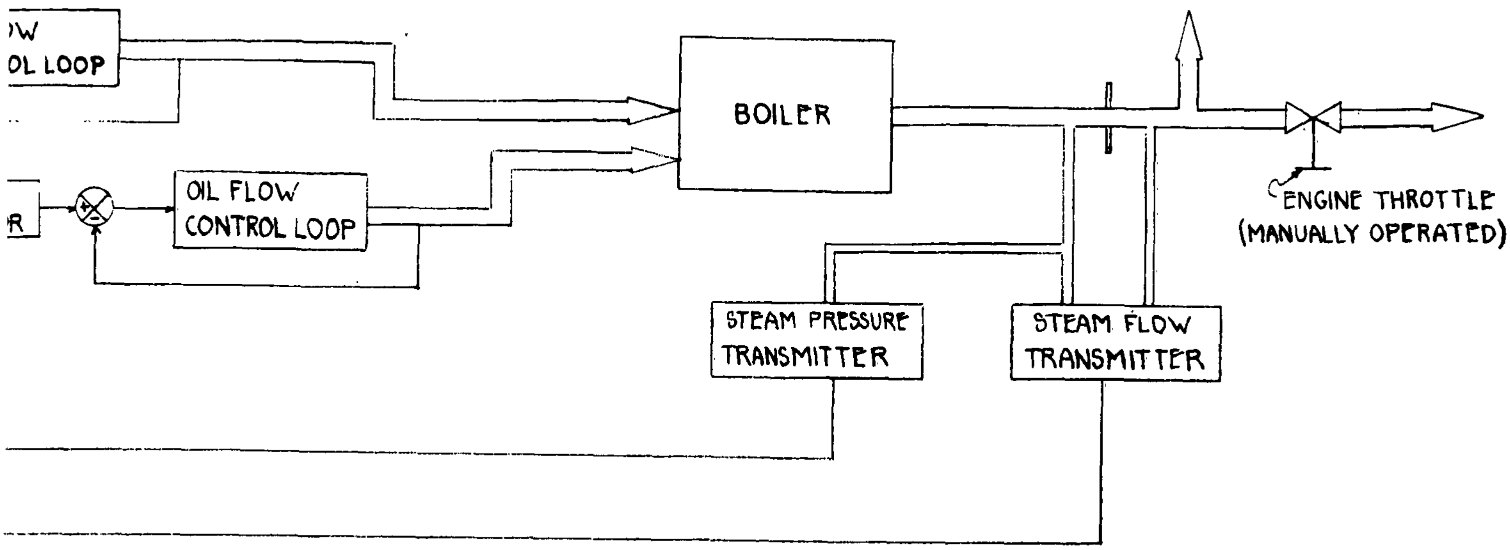


DIAGRAMMATIC ARRANGEMENT
CONVENTIONAL BO

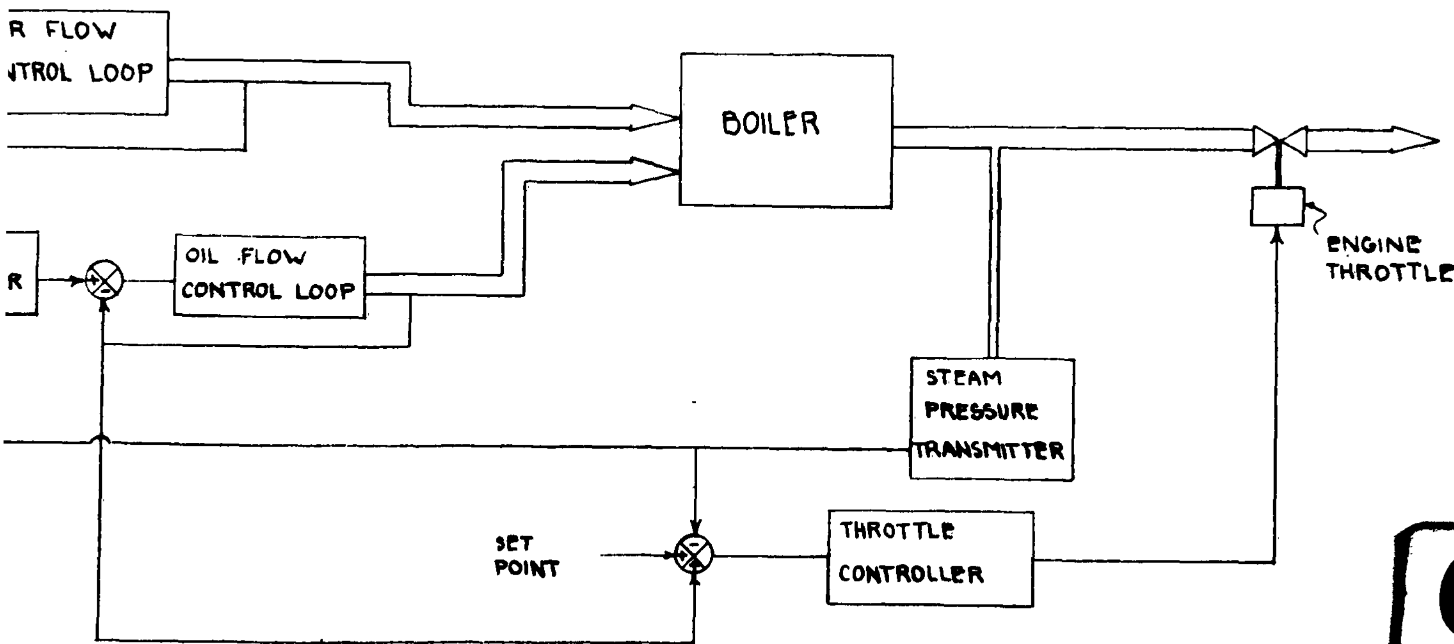


DIAGRAMMATIC ARRANGEMENT
TURBINE-FOL

1

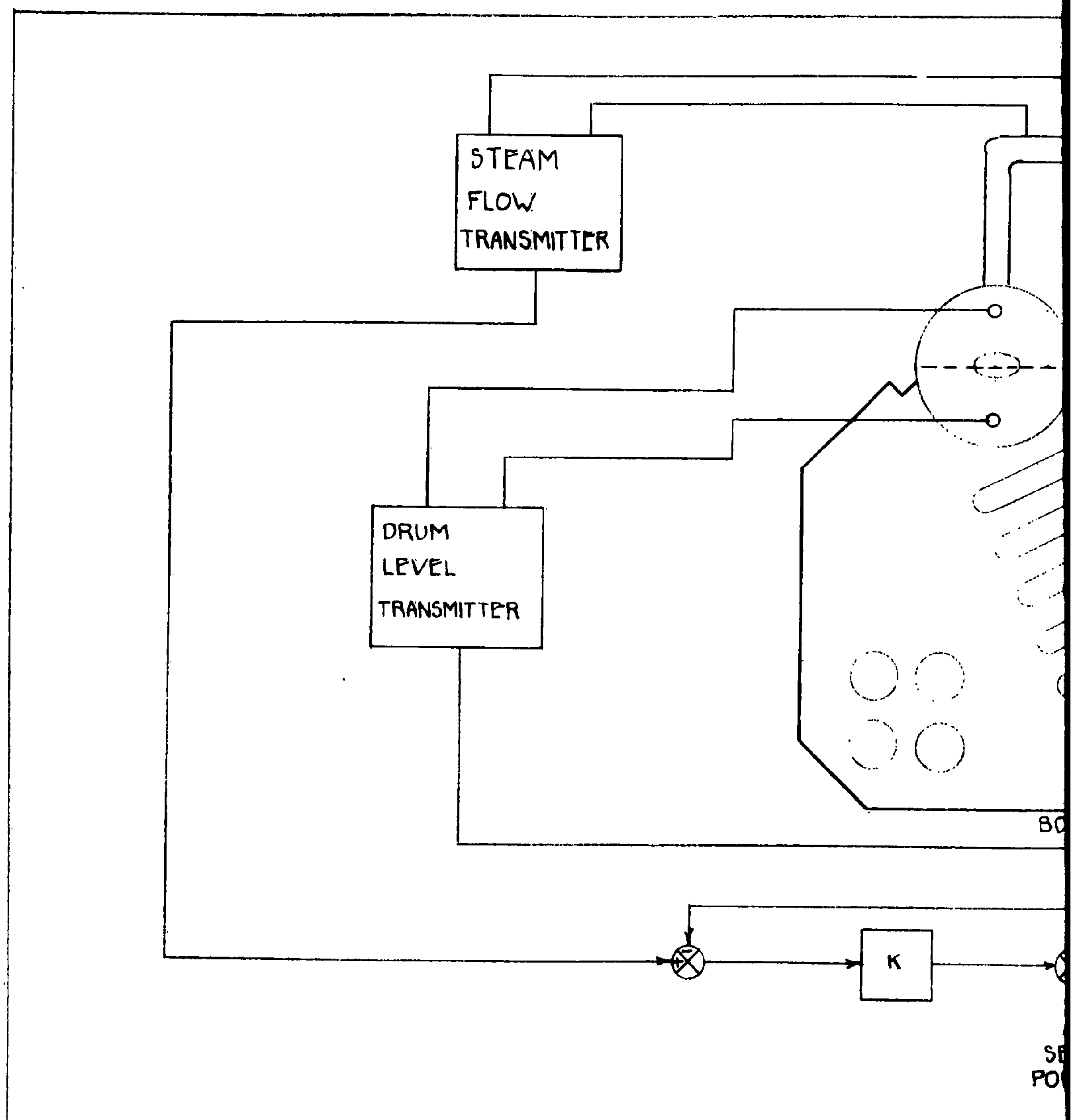


IC ARRANGEMENT OF MACHINERY AND CONTROLS
CONVENTIONAL BOILER-FOLLOWER CYCLE



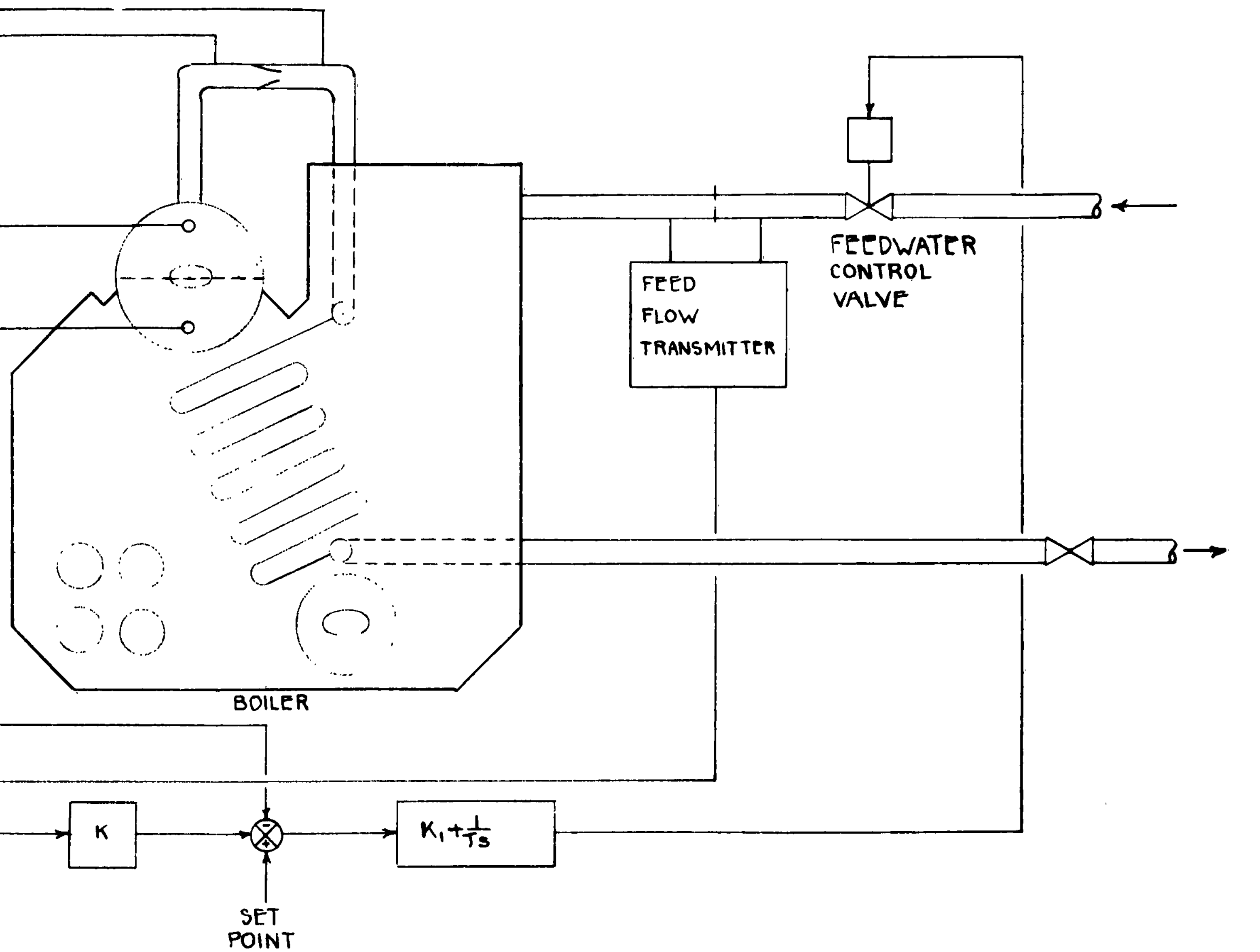
C ARRANGEMENT OF MACHINERY AND CONTROLS
TURBINE-FOLLOWER CYCLE

FIGURE 5



STANDARD NAVY THREE-ELEME
DIAGRAMMATI

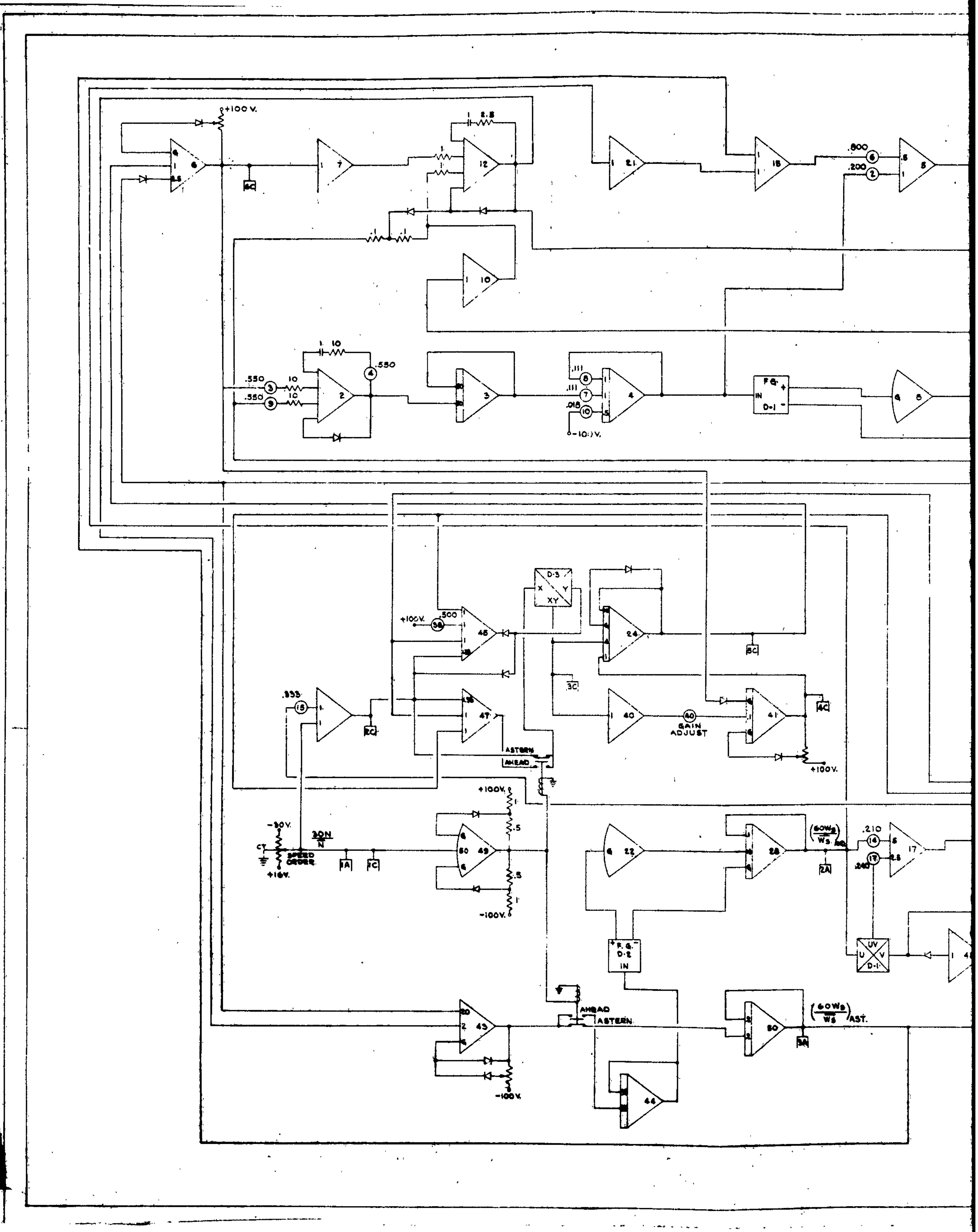
1



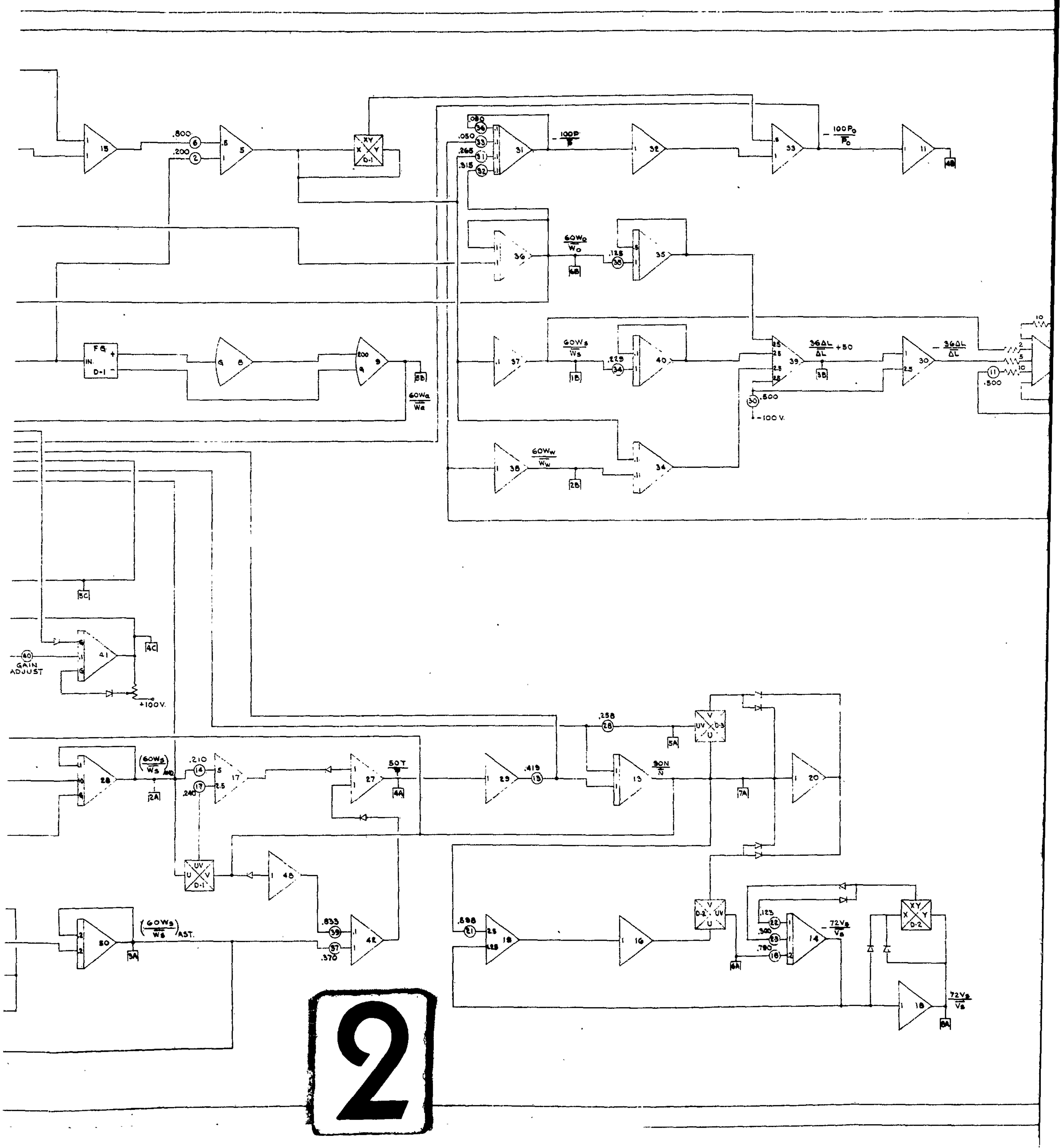
AVY THREE-ELEMENT FEEDWATER CONTROL SYSTEM
DIAGRAMMATIC ARRANGEMENT

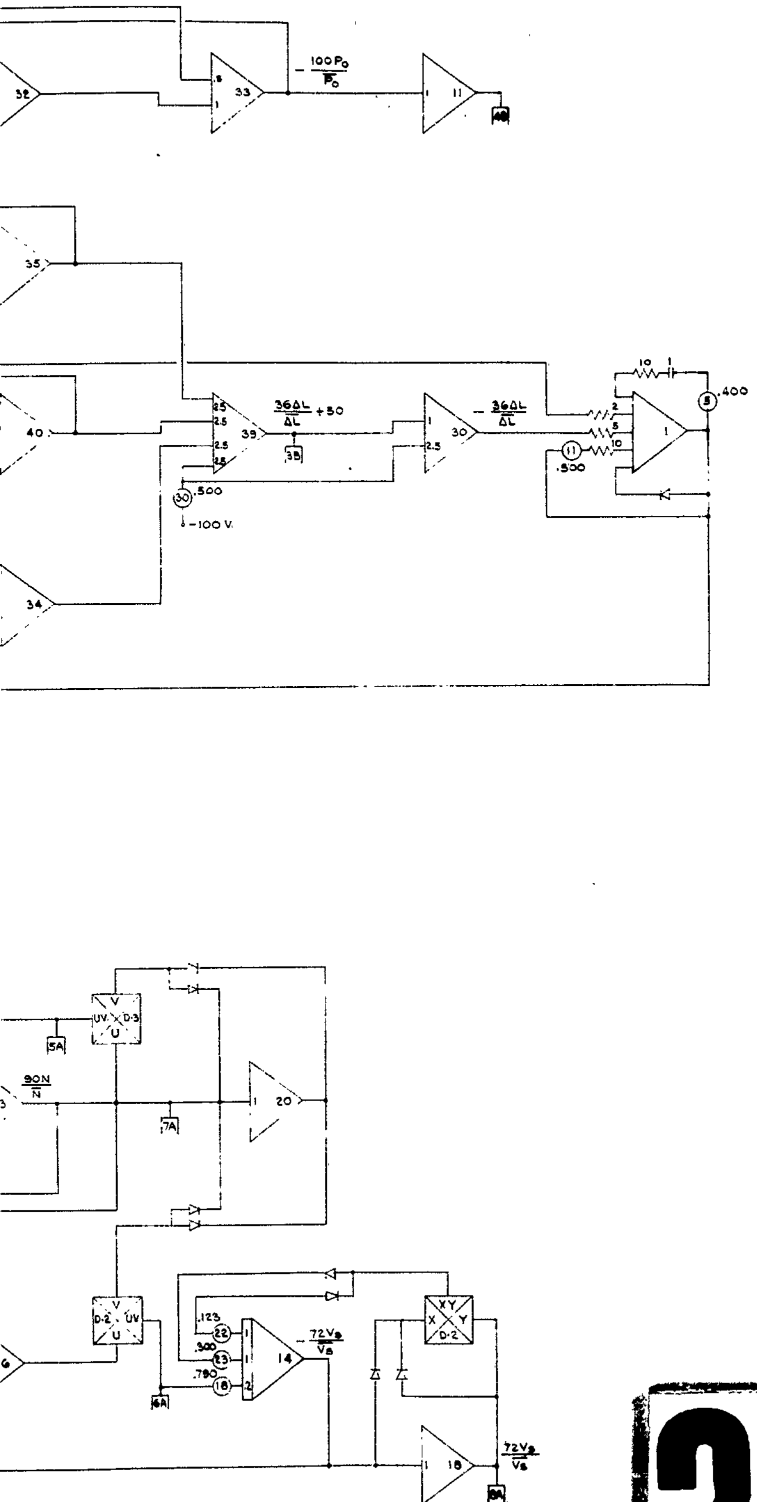
2

FIGURE 6


+100 V.
6C
1 2.5
.800
.200
.550
.550
.550
.111
.111
.018
-10.0 V.
F.G.
D-1
D-3
XY
+100V.
.500
5C
3C
4C
.333
2C
GAIN
ADJUST
ASTERN
AHEAD
+100V.
-30V.
CT
SPEED
ORDER
+16V.
$\frac{30N}{N}$
1A
1C
-100V.
F.G.
D-2
IN
$\left(\frac{60W_S}{W_S}\right)_{AH.}$
2A
.210
.240
UV
D-1
AHEAD
ASTERN
$\left(\frac{60W_S}{W_S}\right)_{AST.}$
3A
-100V.

1


GAIN ADJUST
+100V.
-100 V.
AST.
2



REV.	DESCRIPTION	APP BY	DATE

PHILA. NAVAL SHIPYARD — NAVAL BASE, PHILA. 12, PA.

NAVAL BOILER AND TURBINE LABORATORY

NBTL PROJECT B-511

DIAGRAMMATIC ARRANGEMENT OF ANALOG COMPUTER PROGRAM

INTEGRATED SHAFT SPEED PROPULSION CONTROL SYSTEM

OFFICIAL	SIGNATURE
DRAWN BY	CpO
CHECKED BY	
SECTION ENGINEER	
PROJECT ENGINEER	

APPROVED (CODE 2723)

FOR THE DIRECTOR

DATE 3/14/63

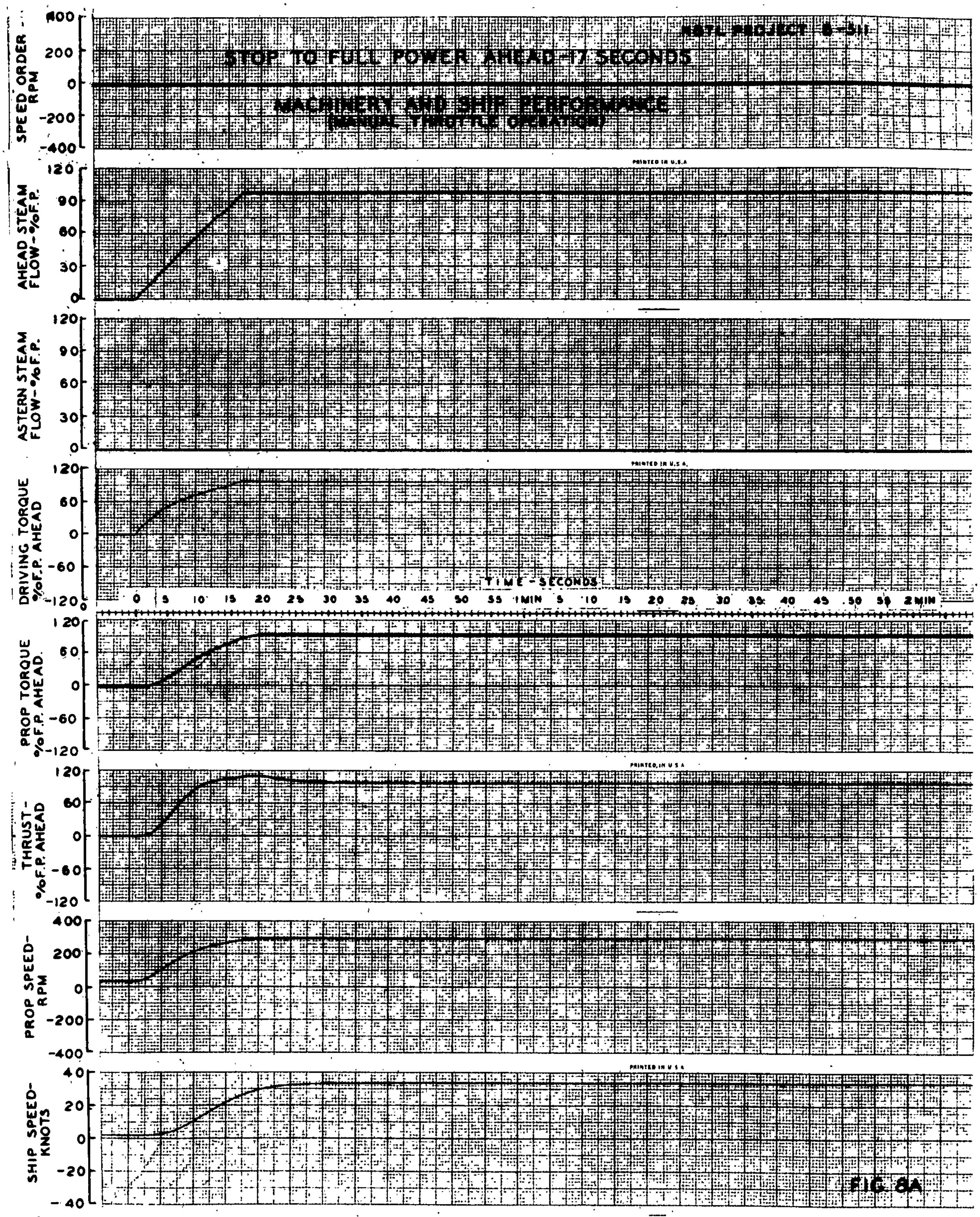
SCALE —

E | O

DWG. NO. 3657

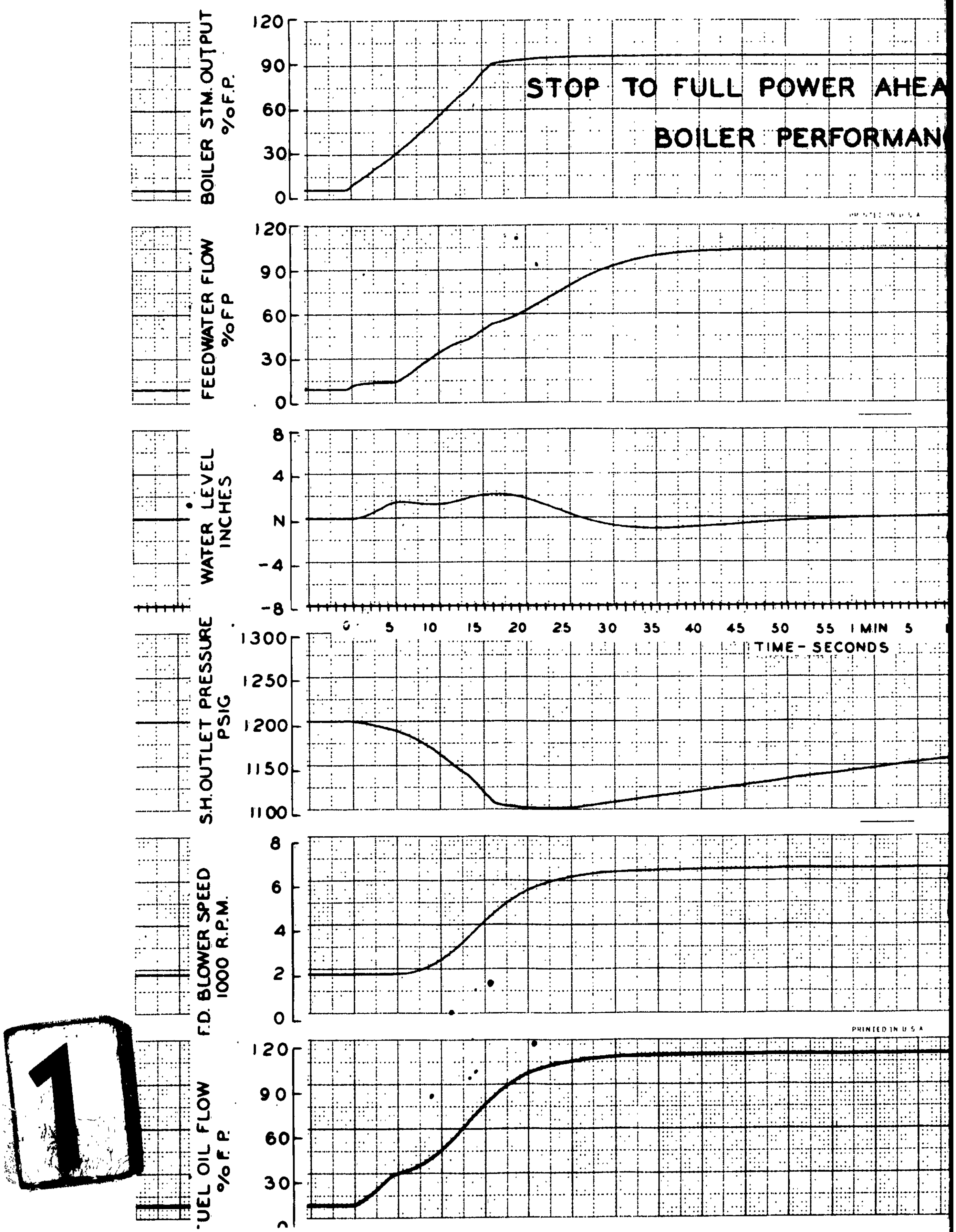
ALT. O

FIGURE 7



STOP TO FULL POWER AHEAD-17 SECONDS
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE OPERATION)
SPEED ORDER - RPM
400
200
0
-200
-400
AHEAD STEAM FLOW-%F.P.
120
90
60
30
0
ASTERN STEAM FLOW-%F.P.
120
90
60
30
0
DRIVING TORQUE %F.P. AHEAD
120
60
0
-60
-120
TIME - SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
PROP TORQUE %F.P. AHEAD
120
60
0
-60
-120
THRUST - %F.P. AHEAD
120
60
0
-60
-120
PROP SPEED - RPM
400
200
0
-200
-400
SHIP SPEED - KNOTS
40
20
0
-20
-40

FIG. 8A



STOP TO FULL POWER AHEA
BOILER PERFORMAN
BOILER STM. OUTPUT %o F.P.
FEEDWATER FLOW %o F P
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
UEL OIL FLOW %o F. P.
TIME - SECONDS
1 MIN
PRINTED IN U.S.A.
1

NBTL PROJECT B-511

STOP TO FULL POWER AHEAD-17 SECONDS

BOILER PERFORMANCE

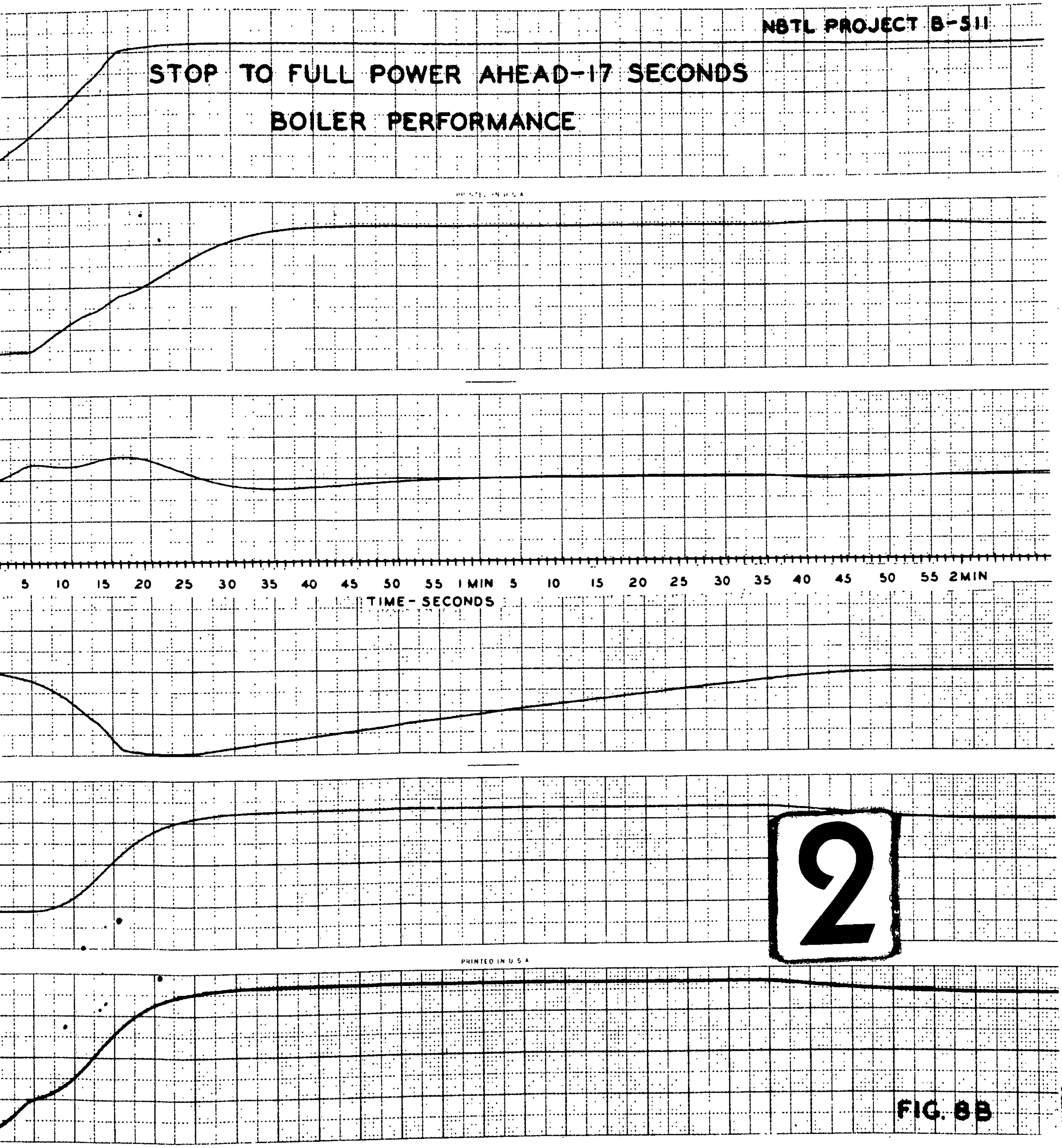
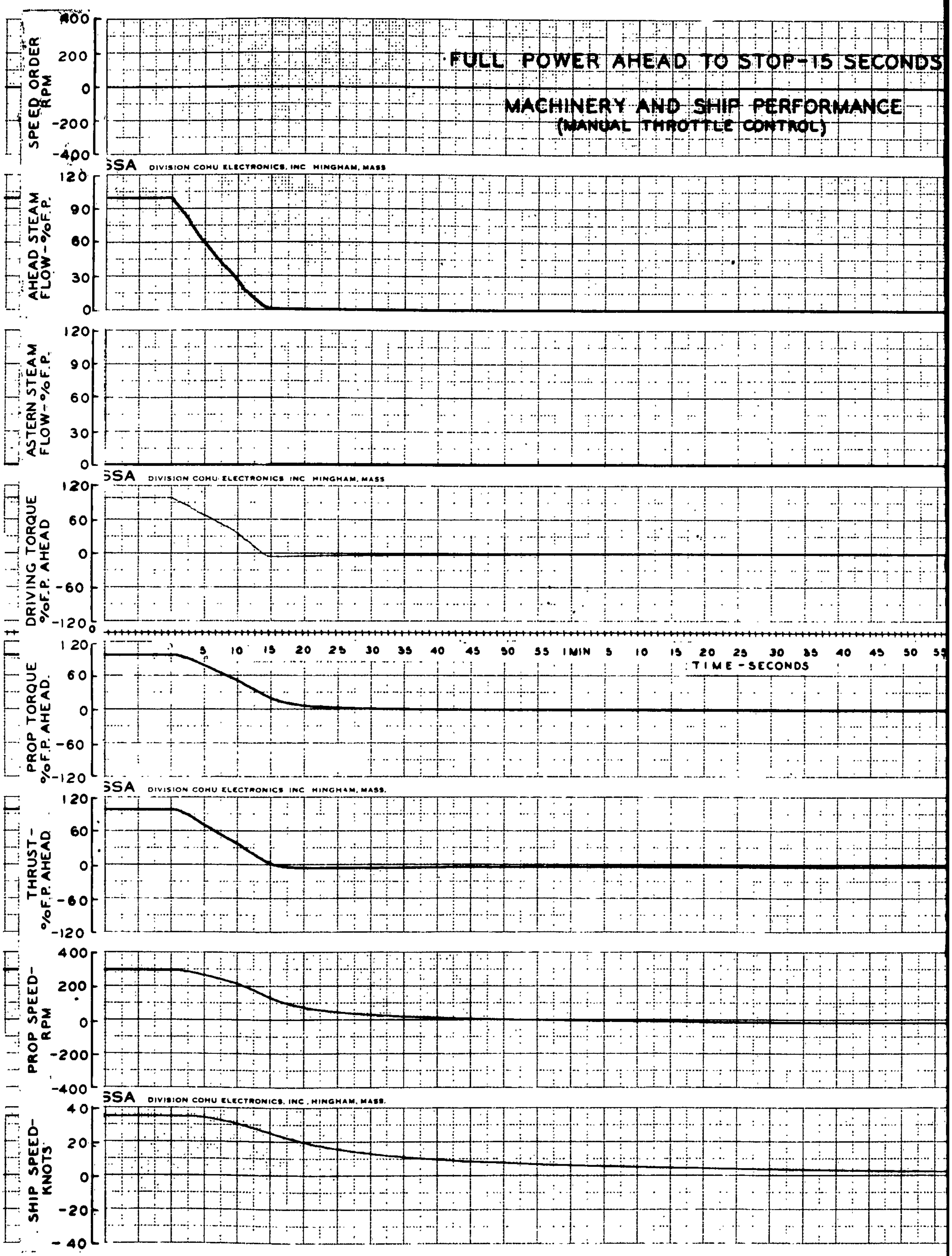


FIG. 8B


FULL POWER AHEAD TO STOP-15 SECONDS
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD
THRUST- %F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
TIME-SECONDS
SSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.

1

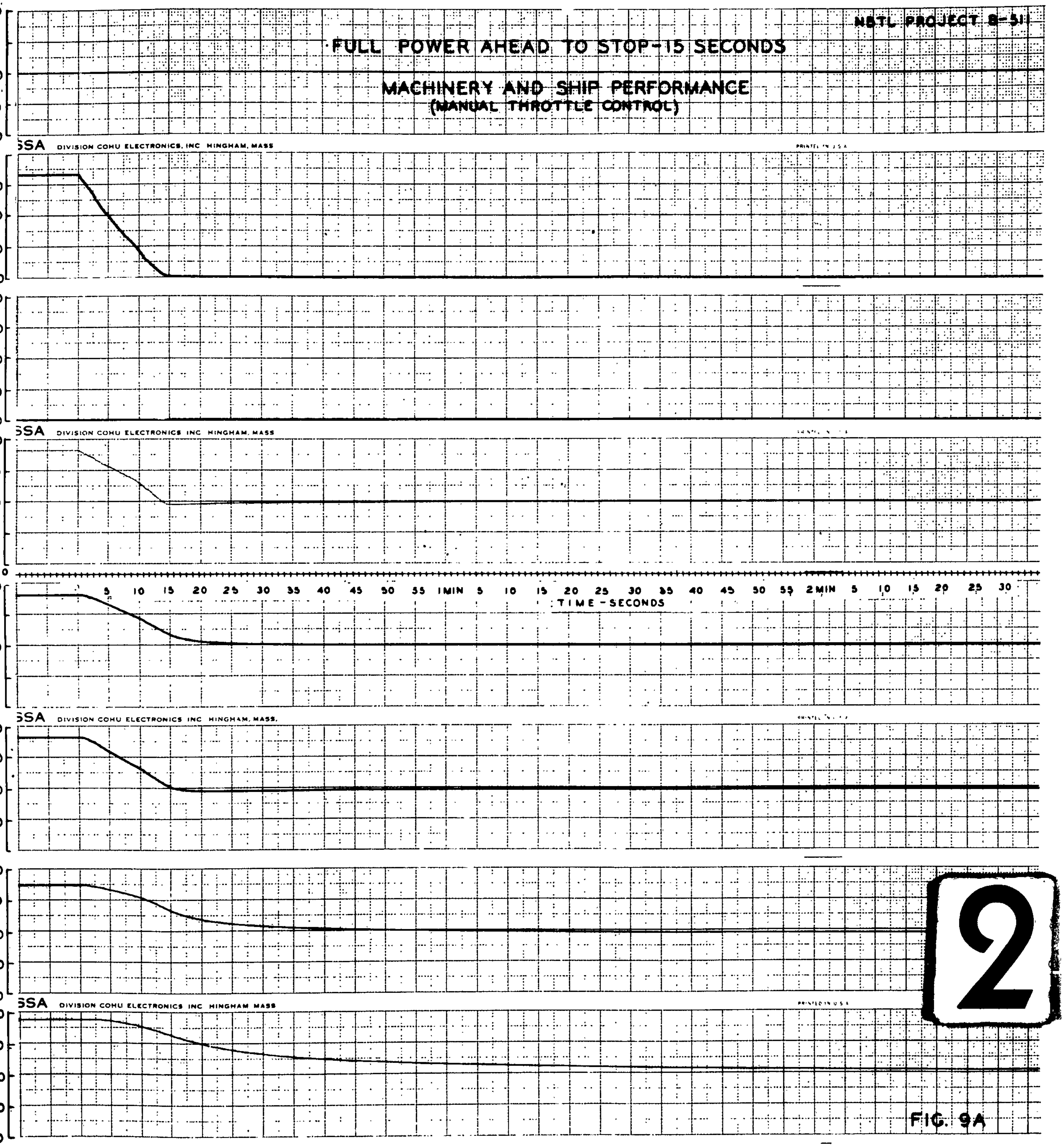
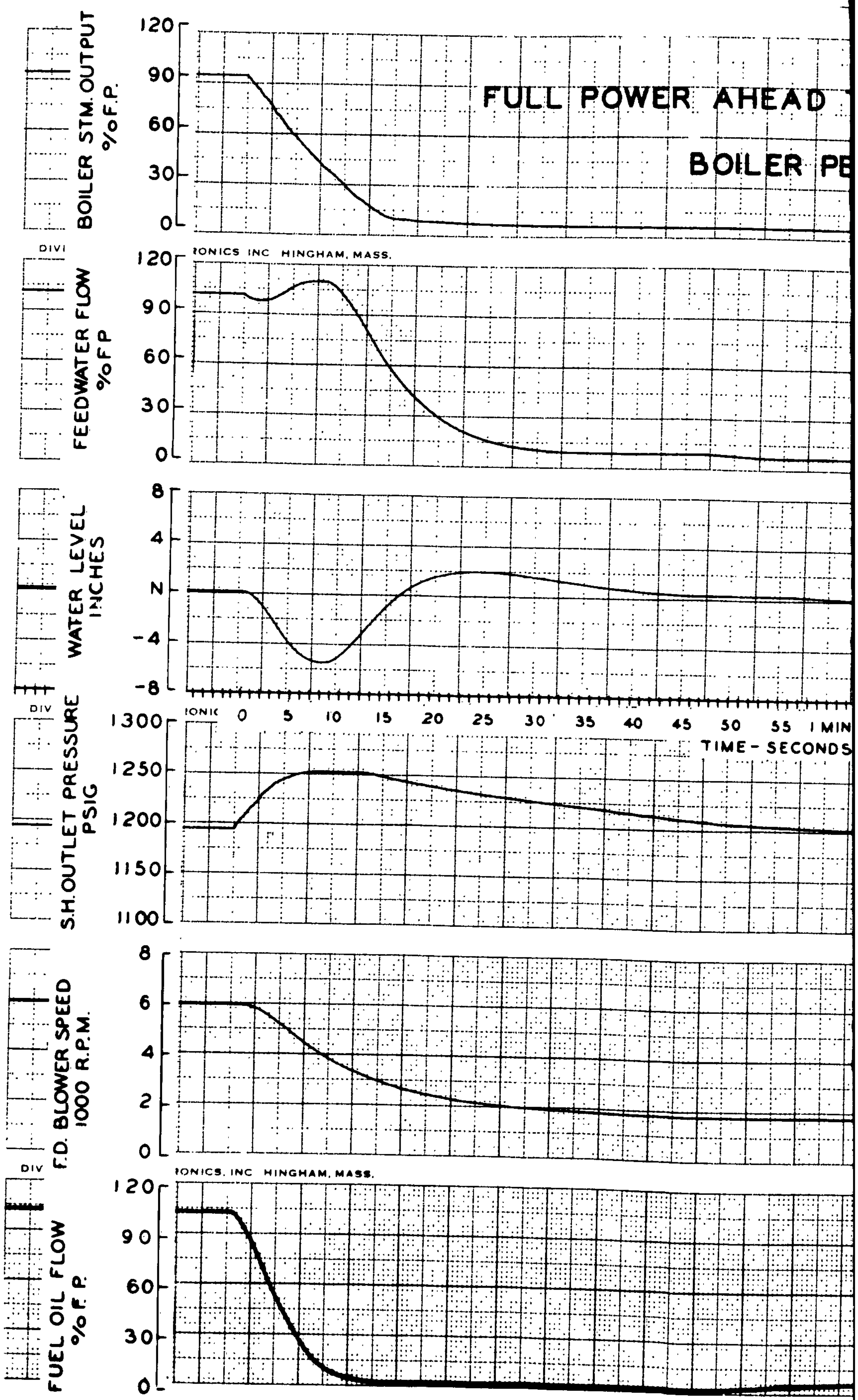

NBTL PROJECT B-511
FULL POWER AHEAD TO STOP-15 SECONDS
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE CONTROL)
SSA DIVISION COHU ELECTRONICS, INC HINGHAM, MASS
5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN 5 10 15 20 25 30
TIME - SECONDS
2

FIG. 9A


FULL POWER AHEAD T
BOILER PE
BOILER STM. OUTPUT %oF.P.
FEEDWATER FLOW %FP
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %F.P.
TIME - SECONDS
IONICS INC HINGHAM, MASS.
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN
120 90 60 30 0
8 4 N -4 -8
1300 1250 1200 1150 1100
8 6 4 2 0

1

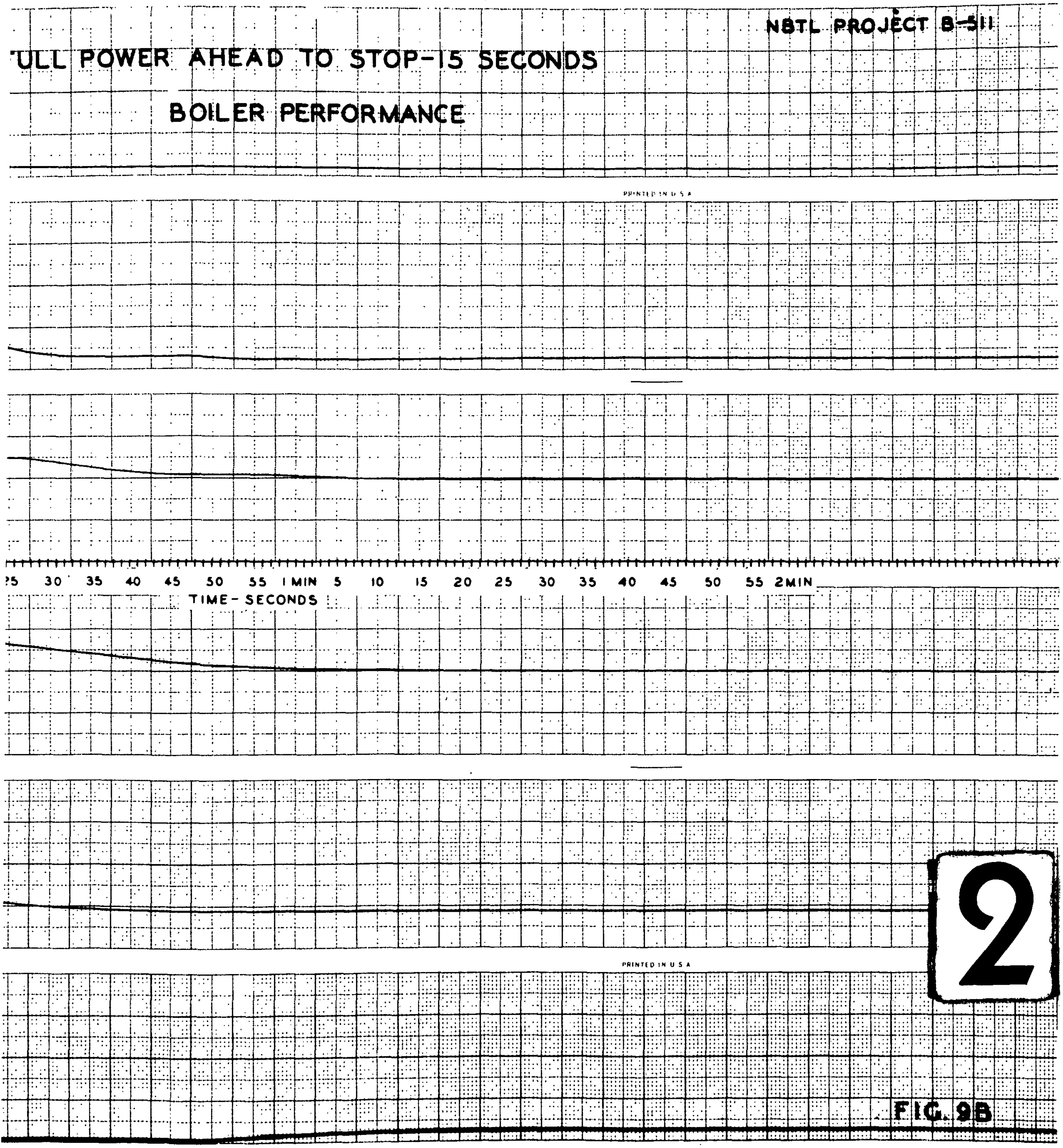
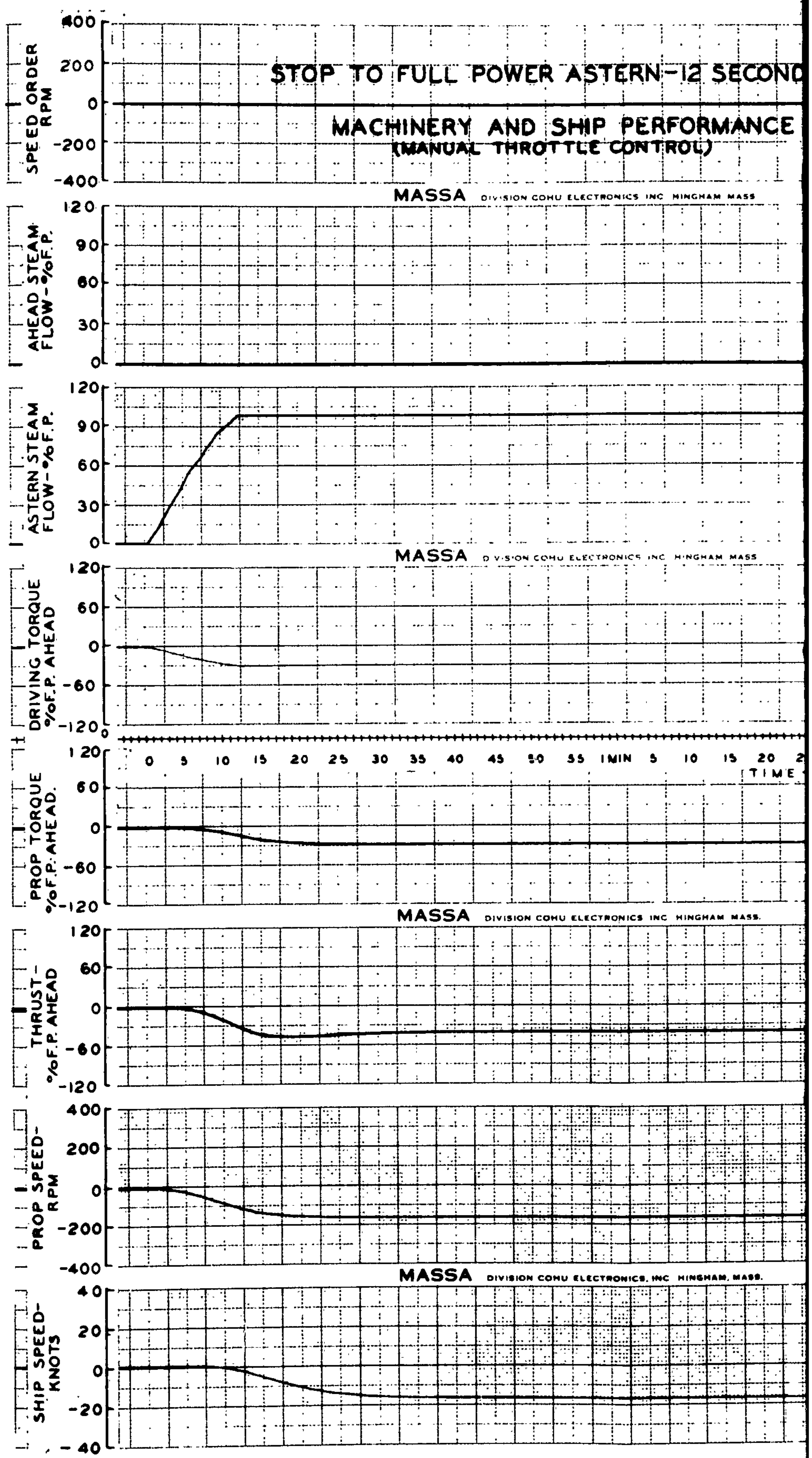
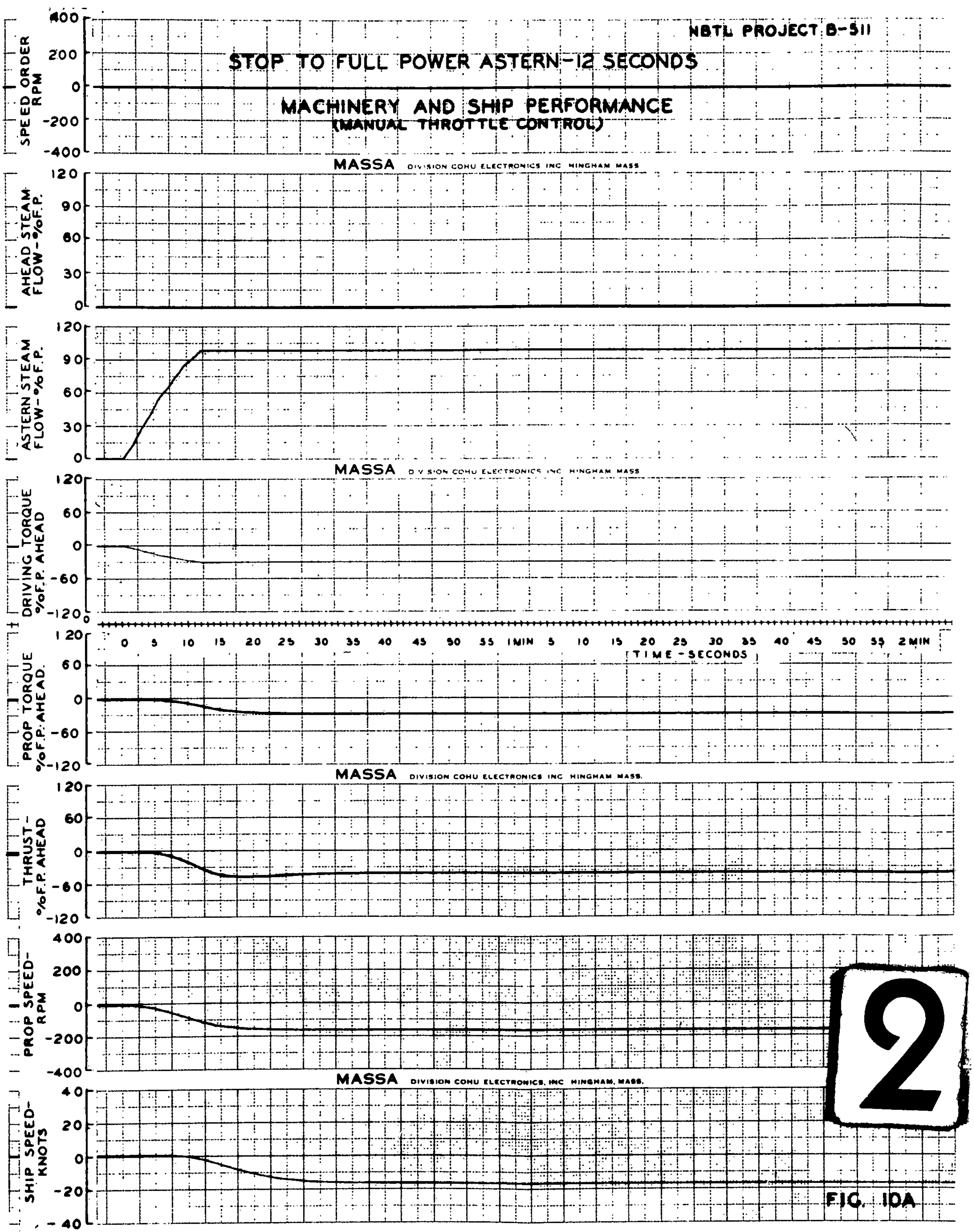
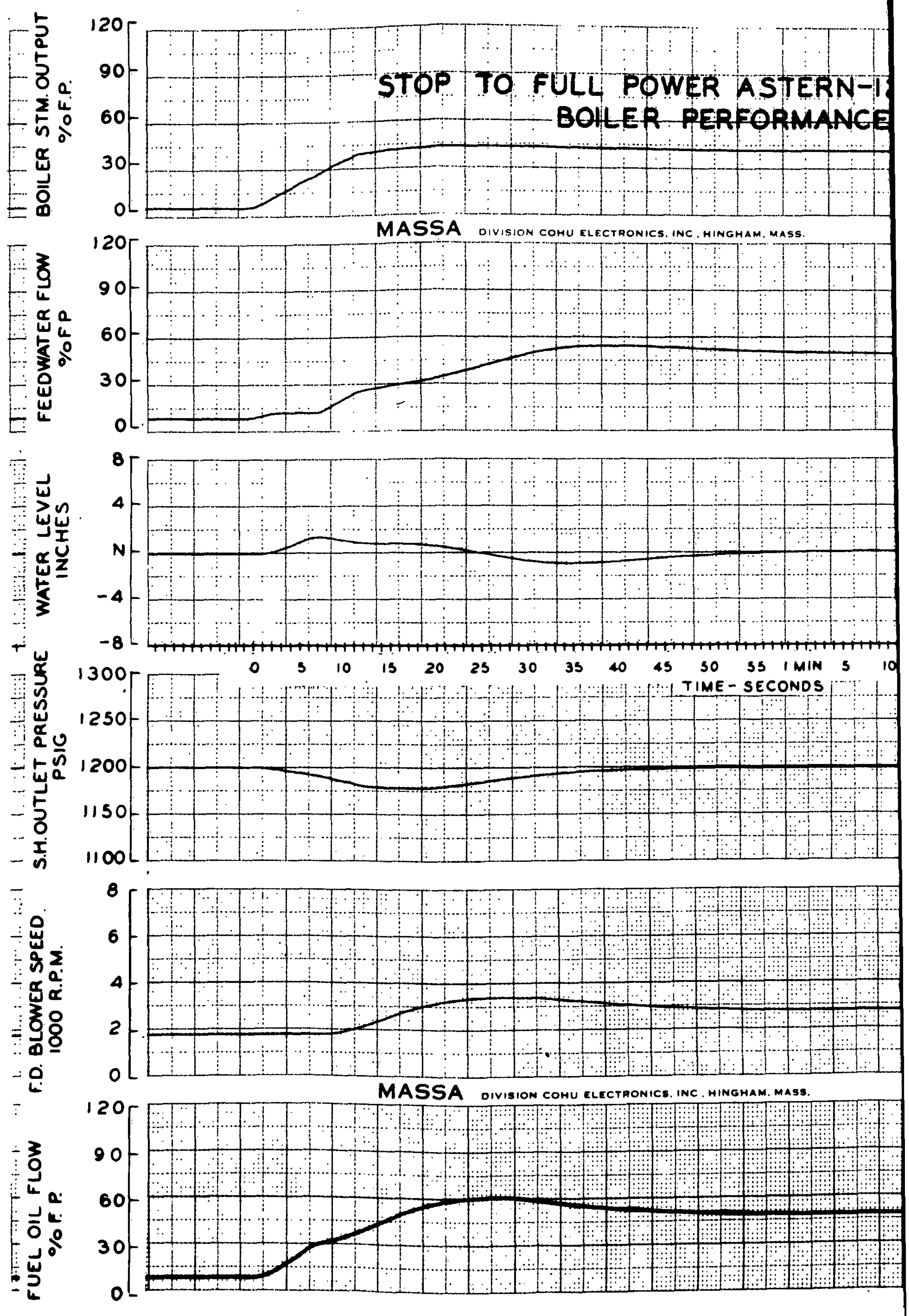

NBTL PROJECT B-511
ULL POWER AHEAD TO STOP-15 SECONDS
BOILER PERFORMANCE
25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME- SECONDS
2

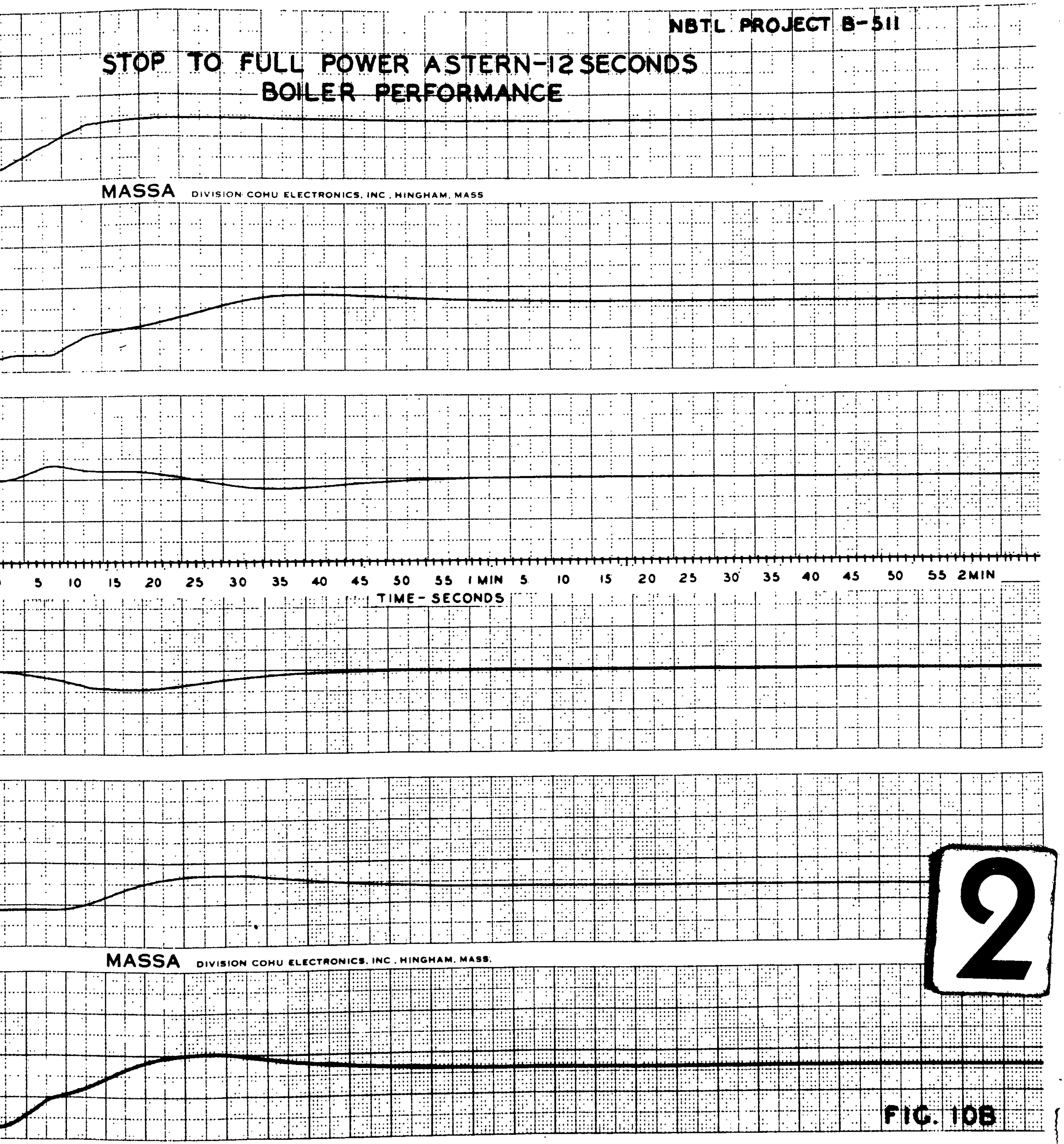
FIG. 9B


STOP TO FULL POWER ASTERN-12 SECOND
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD.
THRUST- %F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20
TIME


NBTL PROJECT B-511
STOP TO FULL POWER ASTERN-12 SECONDS
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%OF.P.
ASTERN STEAM FLOW-%OF.P.
DRIVING TORQUE %OF.P. AHEAD
PROP TORQUE %OF.P. AHEAD.
THRUST-%OF.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME-SECONDS
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS
2
FIG. 10A

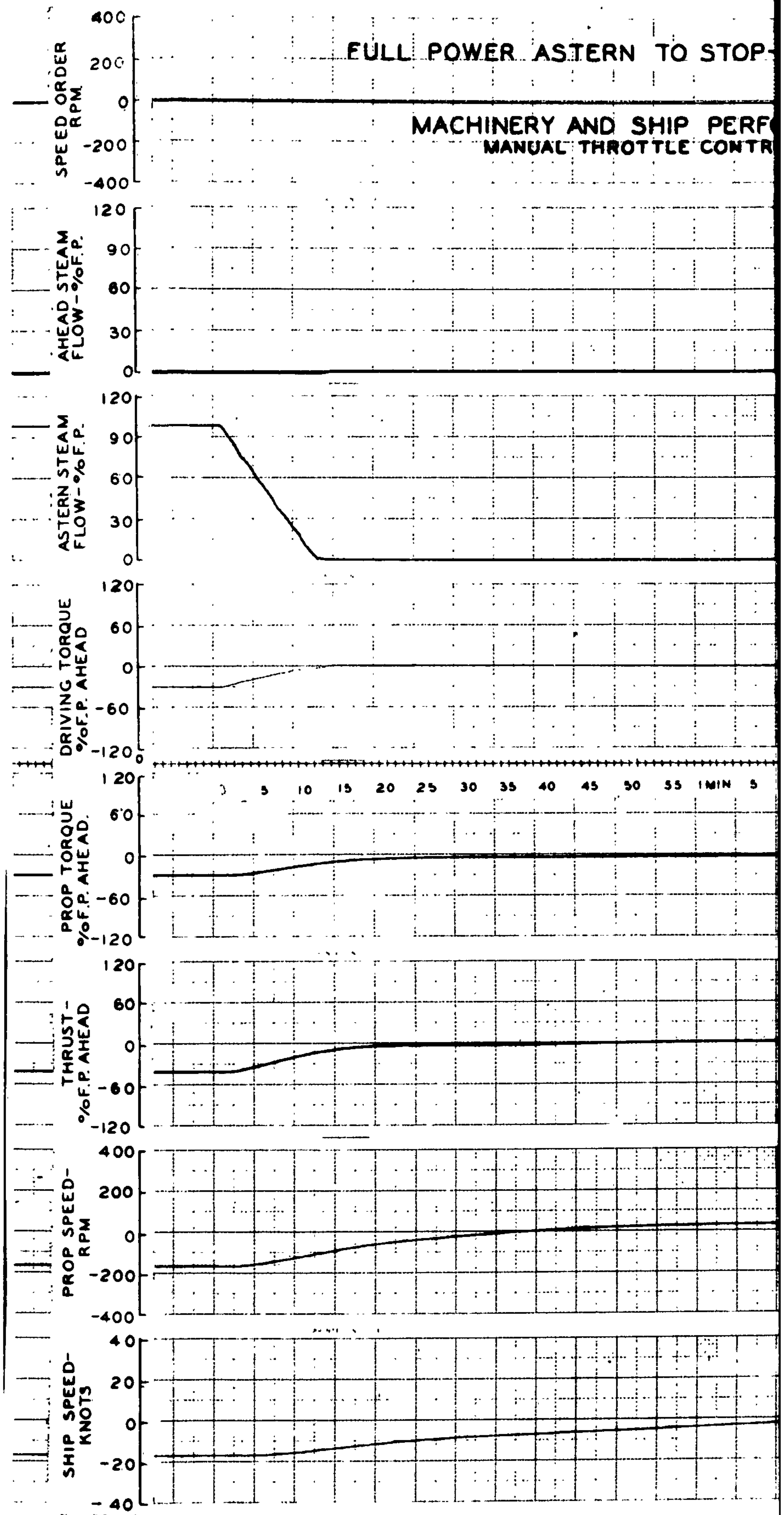

STOP TO FULL POWER ASTERN-1
BOILER PERFORMANCE
BOILER STM. OUTPUT %o F.P.
120
90
60
30
0
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
FEEDWATER FLOW %o F P
120
90
60
30
0
WATER LEVEL INCHES
8
4
N
-4
-8
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10
TIME - SECONDS
S.H. OUTLET PRESSURE PSIG
1300
1250
1200
1150
1100
F.D. BLOWER SPEED 1000 R.P.M.
8
6
4
2
0
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
FUEL OIL FLOW %o F.P.
120
90
60
30
0

1



NBTL PROJECT B-511
STOP TO FULL POWER ASTERN-12 SECONDS
BOILER PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS
5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
2

FIG. 10B



FULL POWER ASTERN TO STOP-
MACHINERY AND SHIP PERF
MANUAL THROTTLE CONTR
SPEED ORDER RPM
AHEAD STEAM FLOW-%of F.P.
ASTERN STEAM FLOW-%of F.P.
DRIVING TORQUE %of F.P. AHEAD
PROP TORQUE %of F.P. AHEAD.
THRUST- %of F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
5 10 15 20 25 30 35 40 45 50 55 1 MIN 5

1

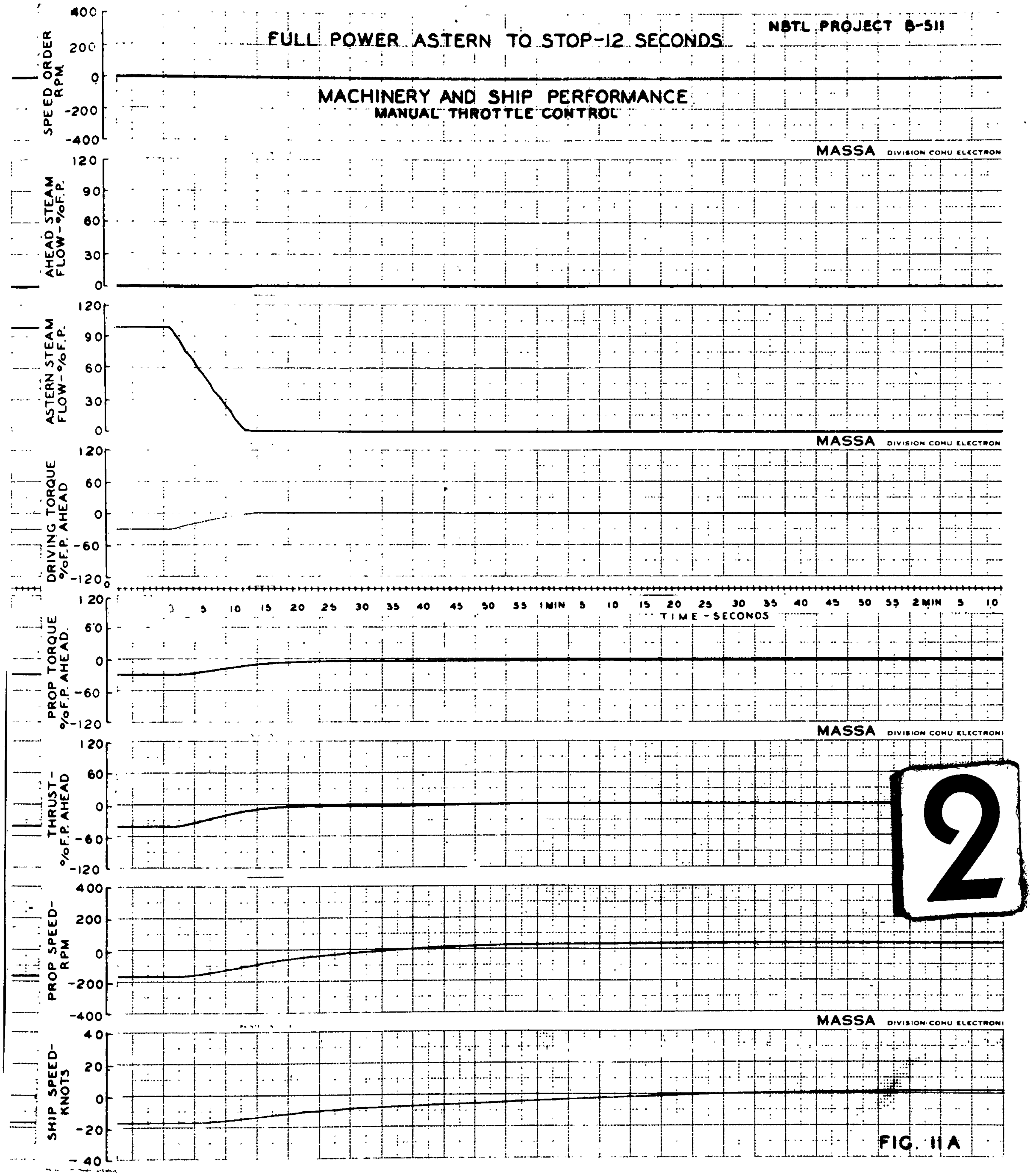
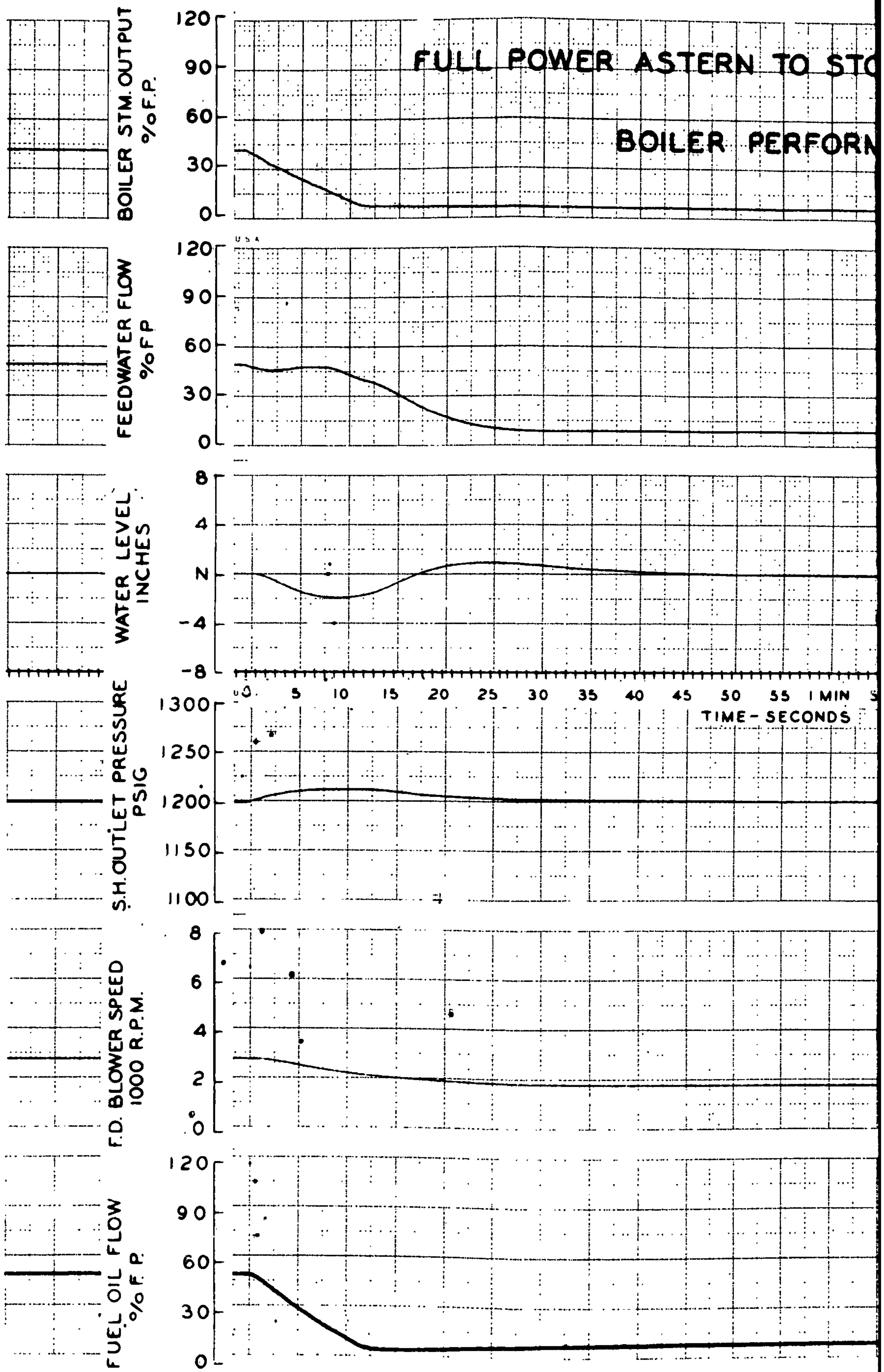
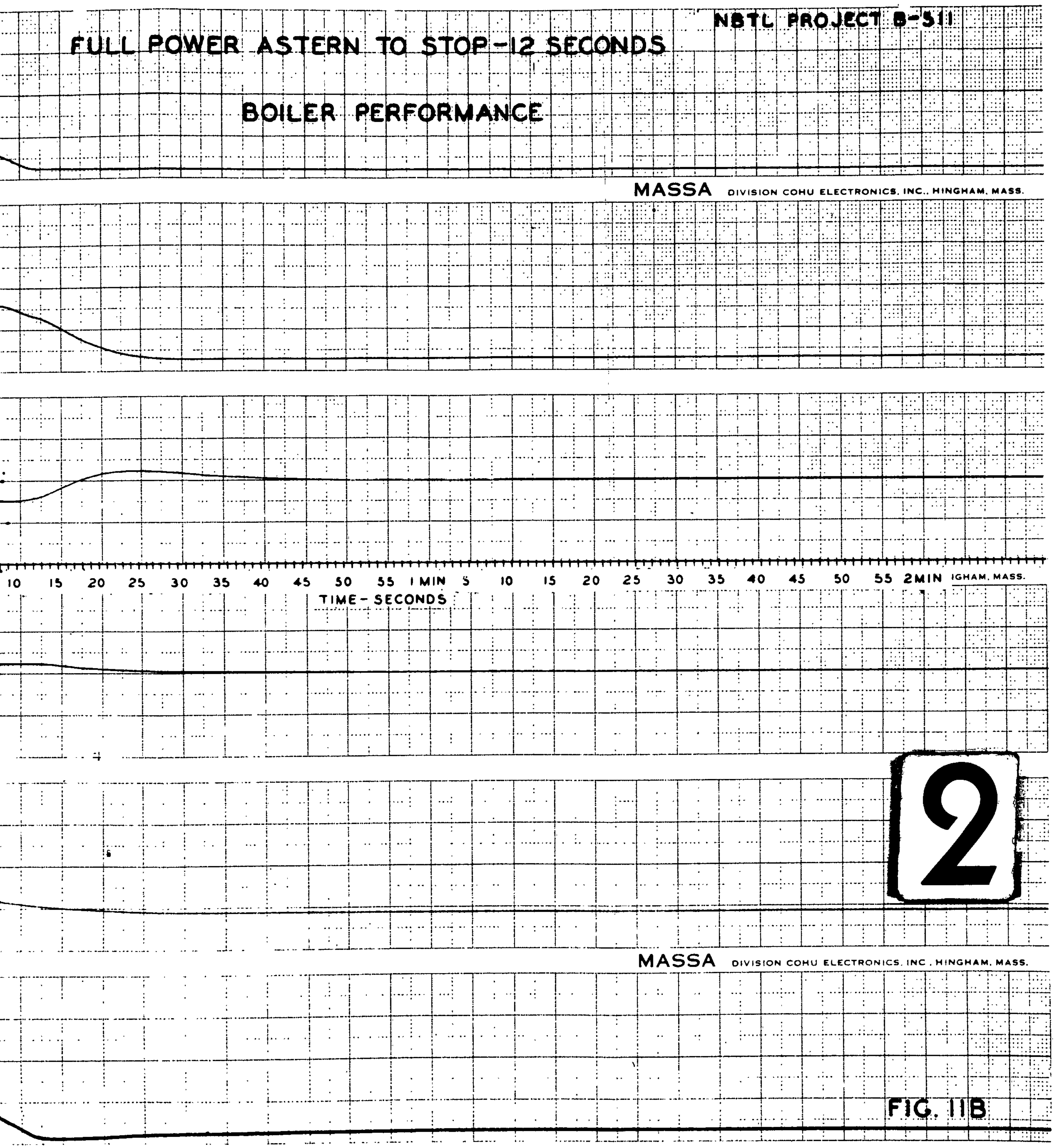

FULL POWER ASTERN TO STOP-12 SECONDS
NBTL PROJECT B-511
MACHINERY AND SHIP PERFORMANCE
MANUAL THROTTLE CONTROL
MASSA DIVISION COHU ELECTRONICS
SPEED ORDER RPM
AHEAD STEAM FLOW-%of F.P.
ASTERN STEAM FLOW-%of F.P.
DRIVING TORQUE %of F.P. AHEAD
PROP TORQUE %of F.P. AHEAD
THRUST-%of F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
TIME-SECONDS
2

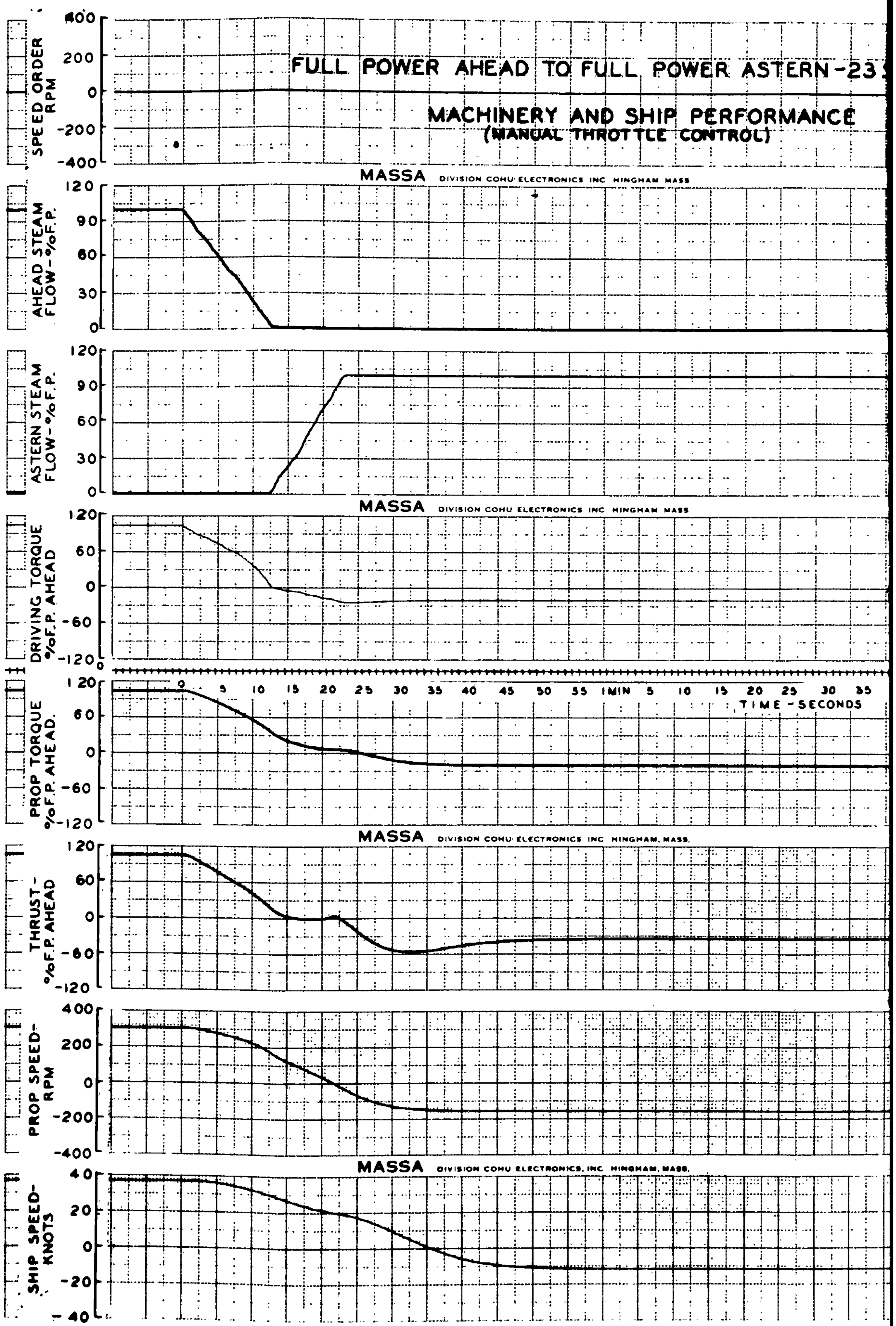
FIG. 11A


FULL POWER ASTERN TO STO
BOILER PERFORM
BOILER STM. OUTPUT %o F.P.
FEEDWATER FLOW %o F.P.
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %o F.P.
TIME - SECONDS
1 MIN



NBTL PROJECT B-511
FULL POWER ASTERN TO STOP-12 SECONDS
BOILER PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
2

FIG. 11B


FULL POWER AHEAD TO FULL POWER ASTERN-23
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD.
THRUST-%F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35
TIME-SECONDS

1

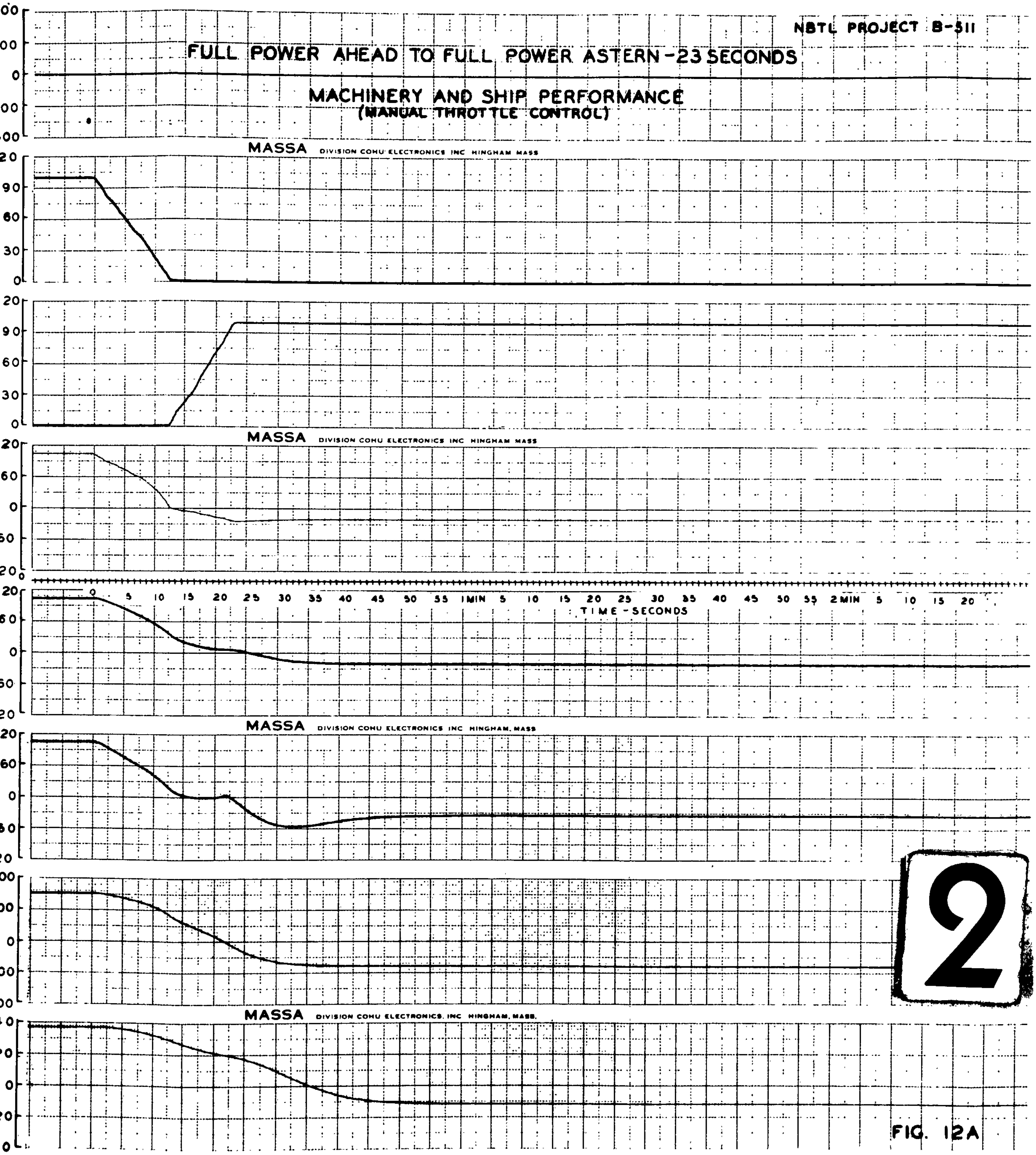
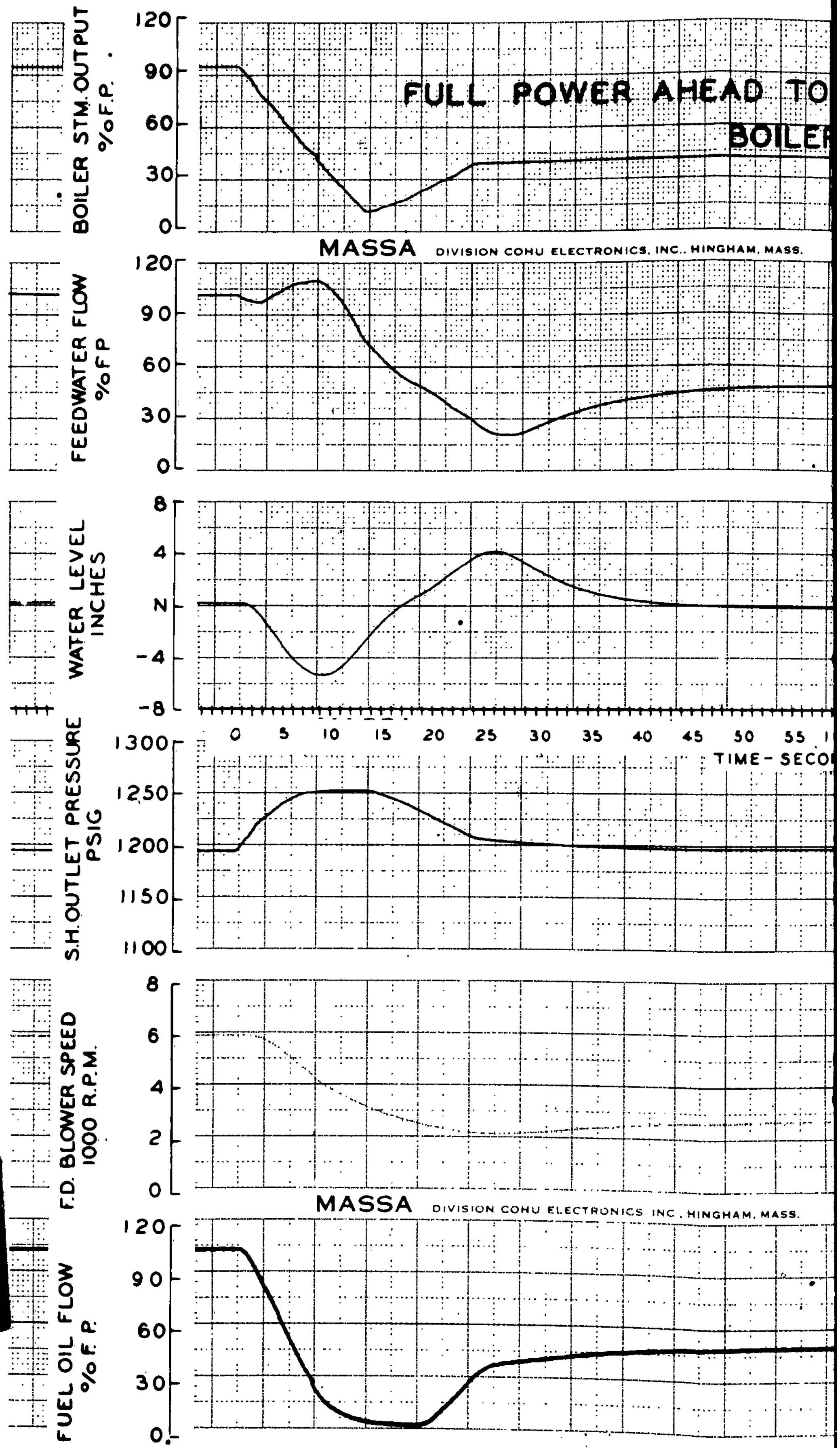

NBTL PROJECT B-511
FULL POWER AHEAD TO FULL POWER ASTERN - 23 SECONDS
MACHINERY AND SHIP PERFORMANCE
(MANUAL THROTTLE CONTROL)
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS
TIME - SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN 5 10 15 20
2

FIG. 12A


FULL POWER AHEAD TO
BOILER STM. OUTPUT %oF.P.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
FEEDWATER FLOW %oFP
WATER LEVEL INCHES
0 5 10 15 20 25 30 35 40 45 50 55
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
MASSA DIVISION COHU ELECTRONICS INC., HINGHAM, MASS.
FUEL OIL FLOW %o F.P.

1

POWER AHEAD TO FULL POWER ASTERN-23 SECONDS
BOILER PERFORMANCE

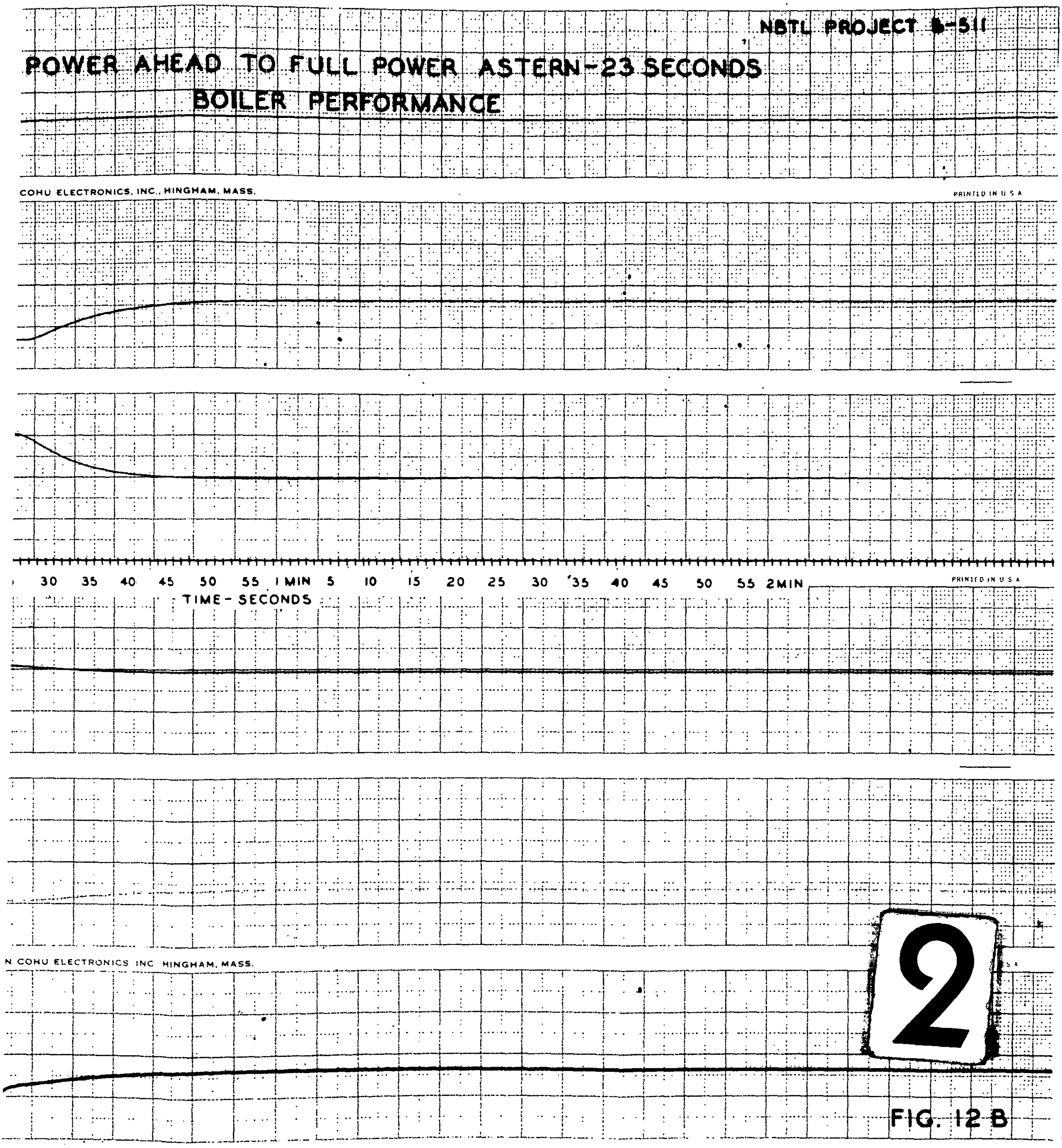


FIG. 12 B

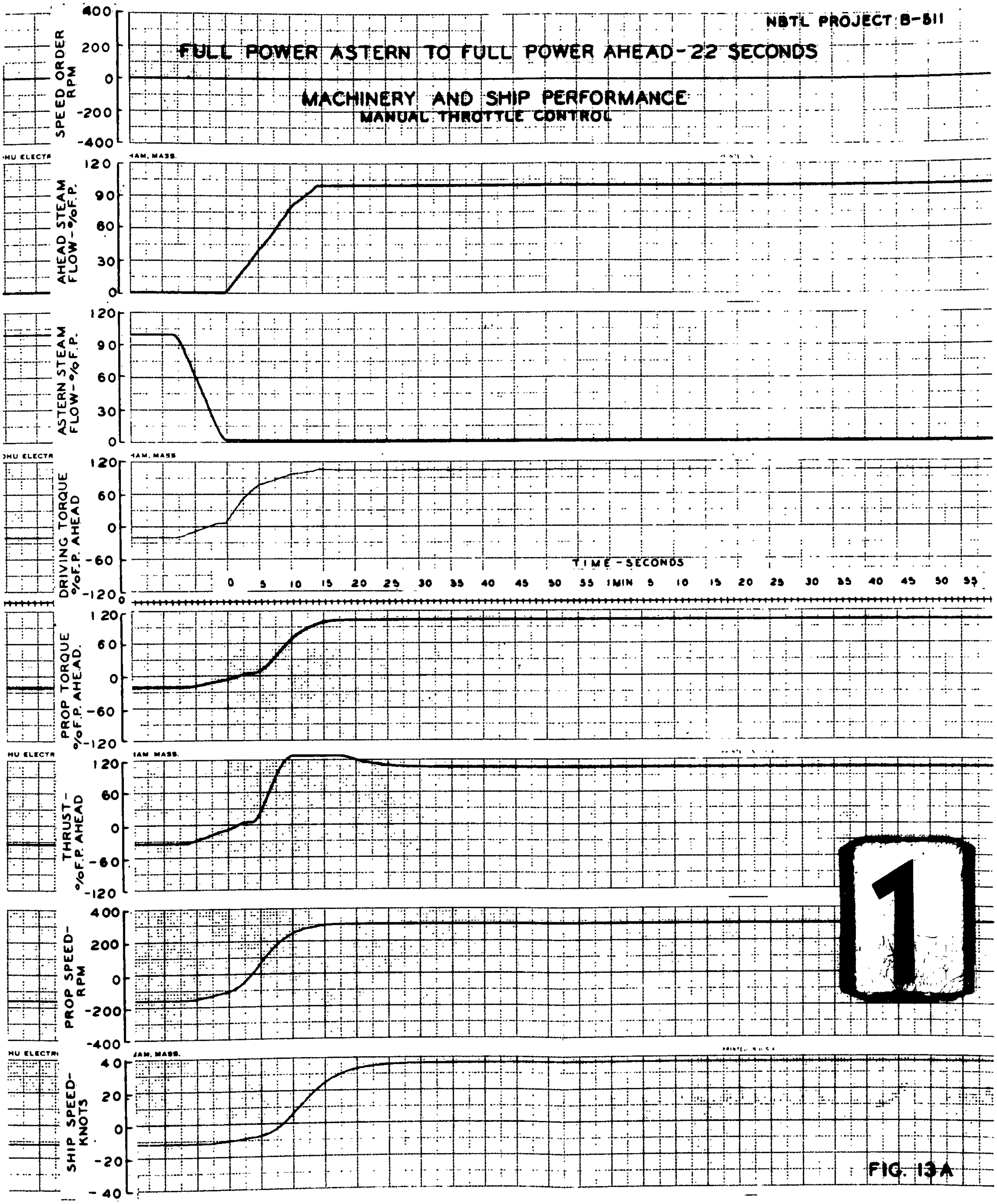
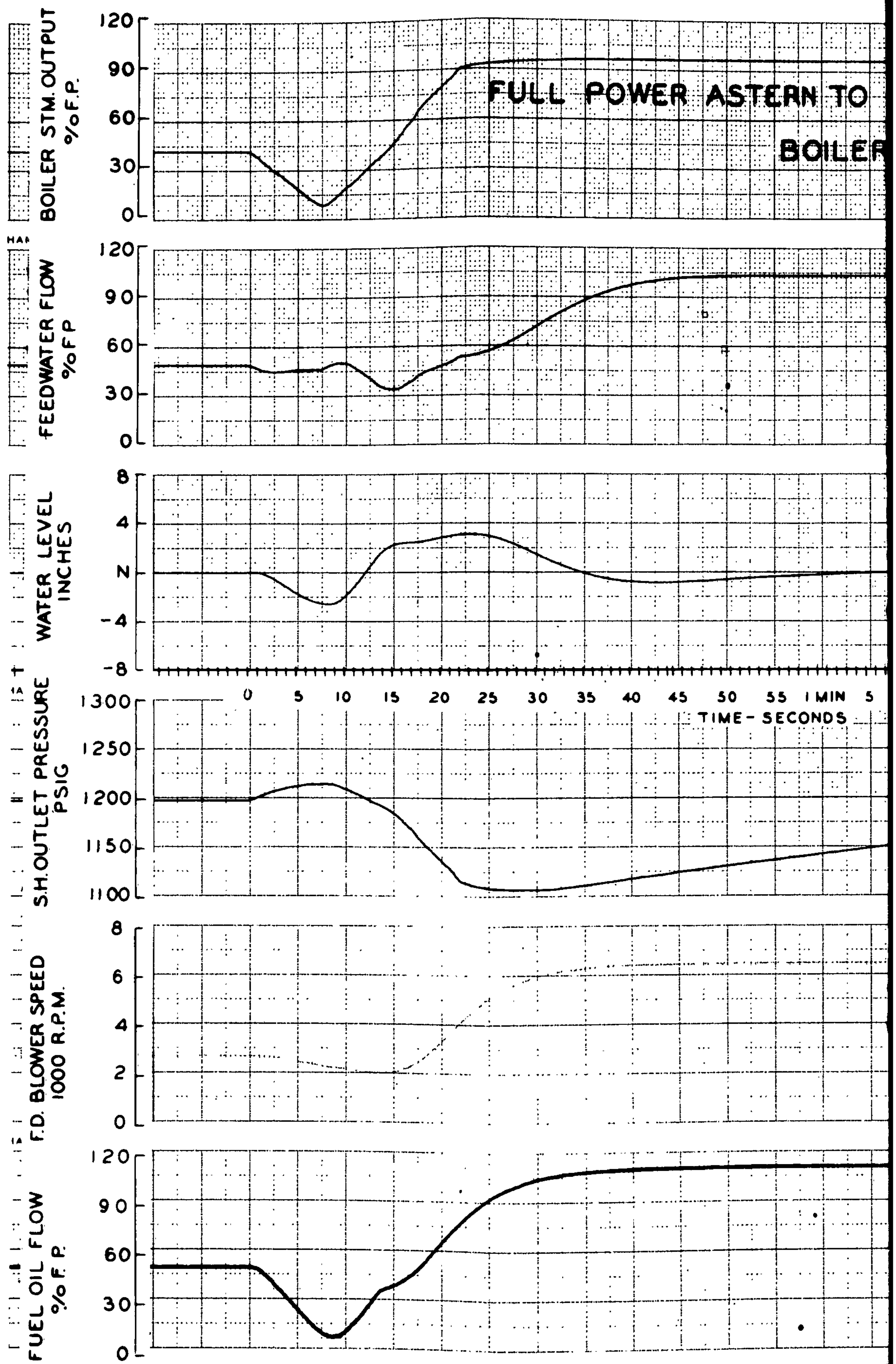

NBTL PROJECT B-511
FULL POWER ASTERN TO FULL POWER AHEAD-22 SECONDS
MACHINERY AND SHIP PERFORMANCE
MANUAL THROTTLE CONTROL
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %OF.P. AHEAD
PROP TORQUE %OF.P. AHEAD.
THRUST-%OF.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
TIME-SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55
1

FIG. 13A

1


FULL POWER ASTERN TO
BOILER
BOILER STM. OUTPUT %o F.P.
120
90
60
30
0
FEEDWATER FLOW %o F P
WATER LEVEL INCHES
8
4
N
-4
-8
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN 5
TIME - SECONDS
S.H. OUTLET PRESSURE PSIG
1300
1250
1200
1150
1100
F.D. BLOWER SPEED 1000 R.P.M.
6
2
FUEL OIL FLOW %o F.P.

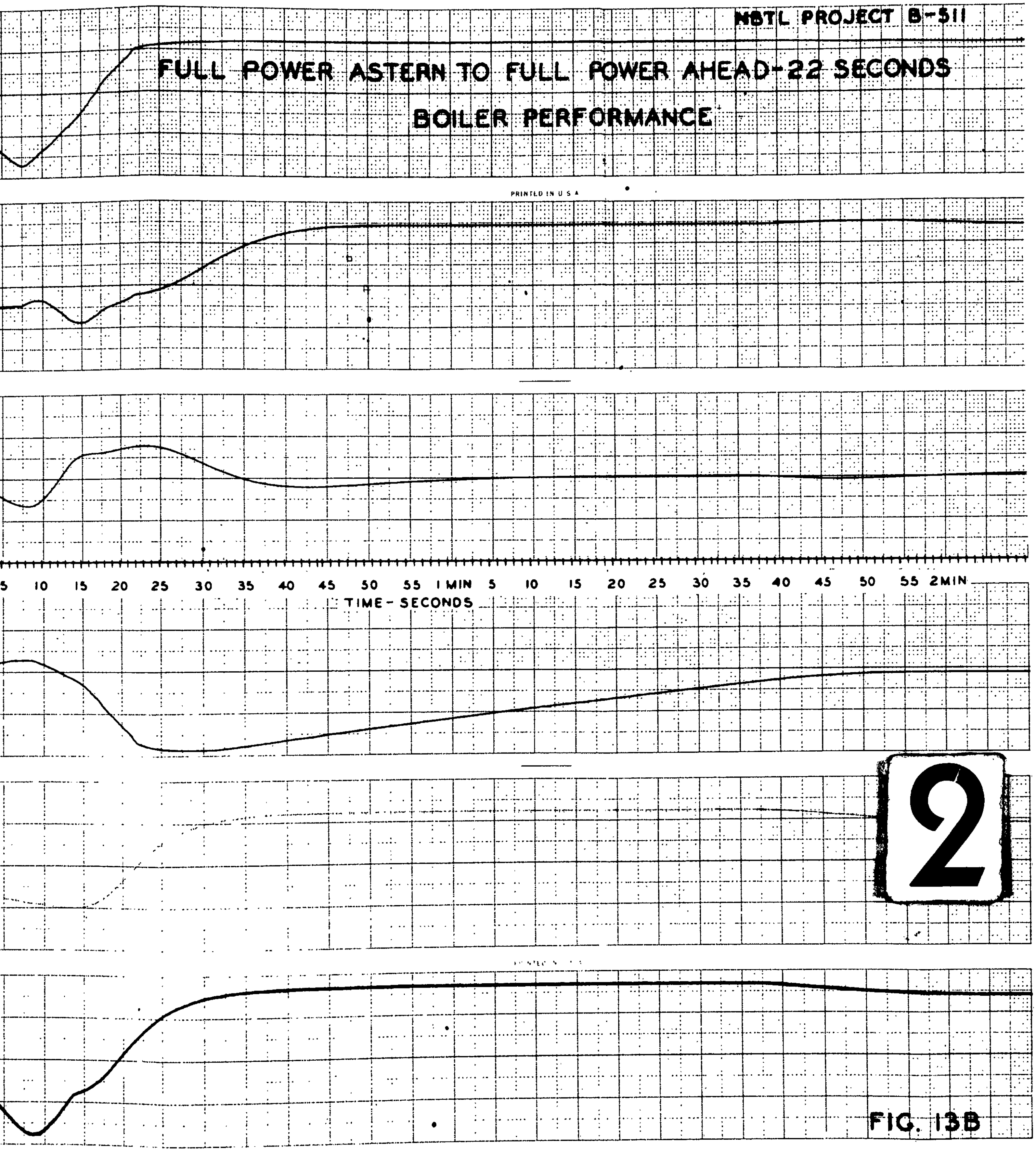
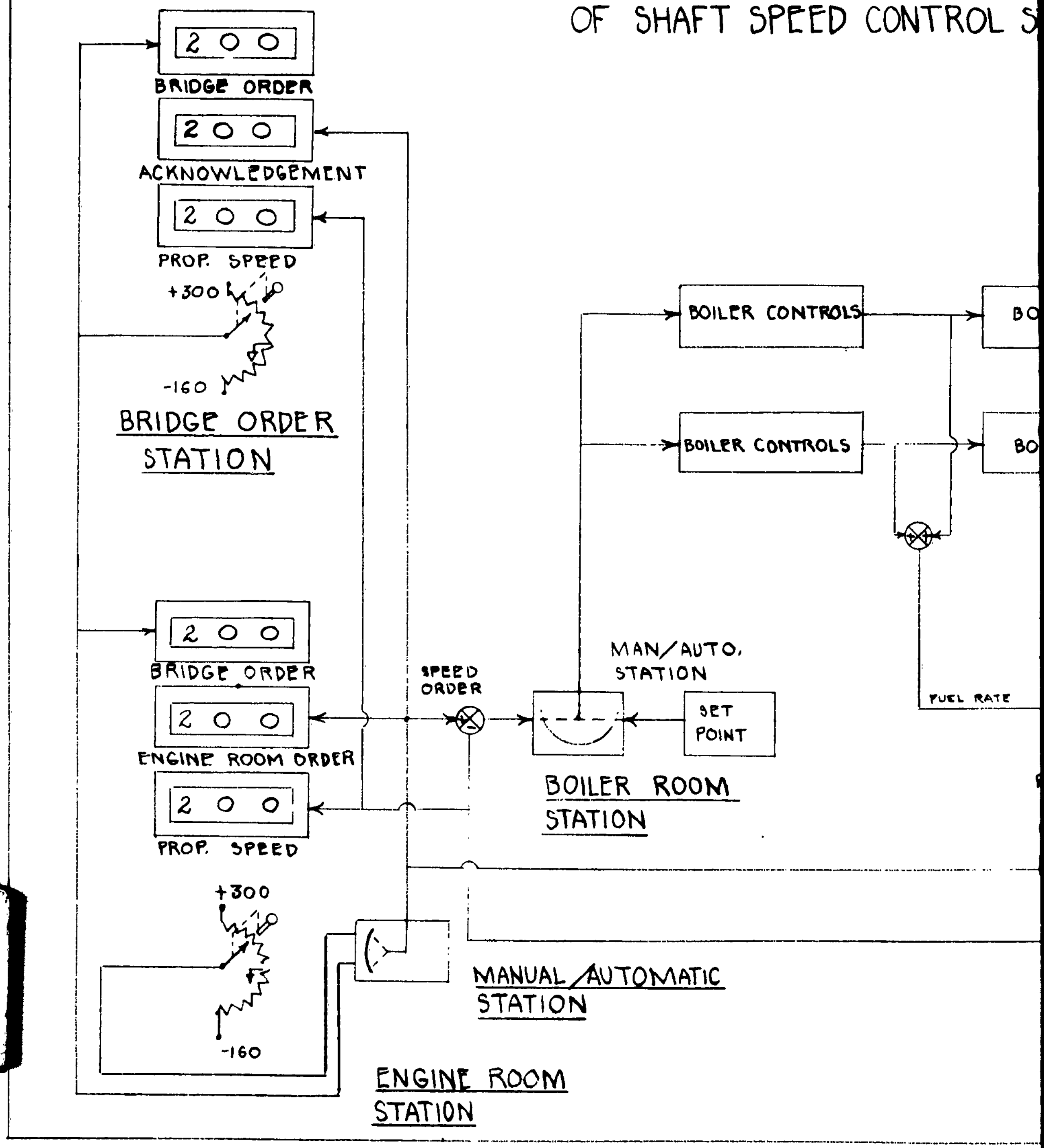
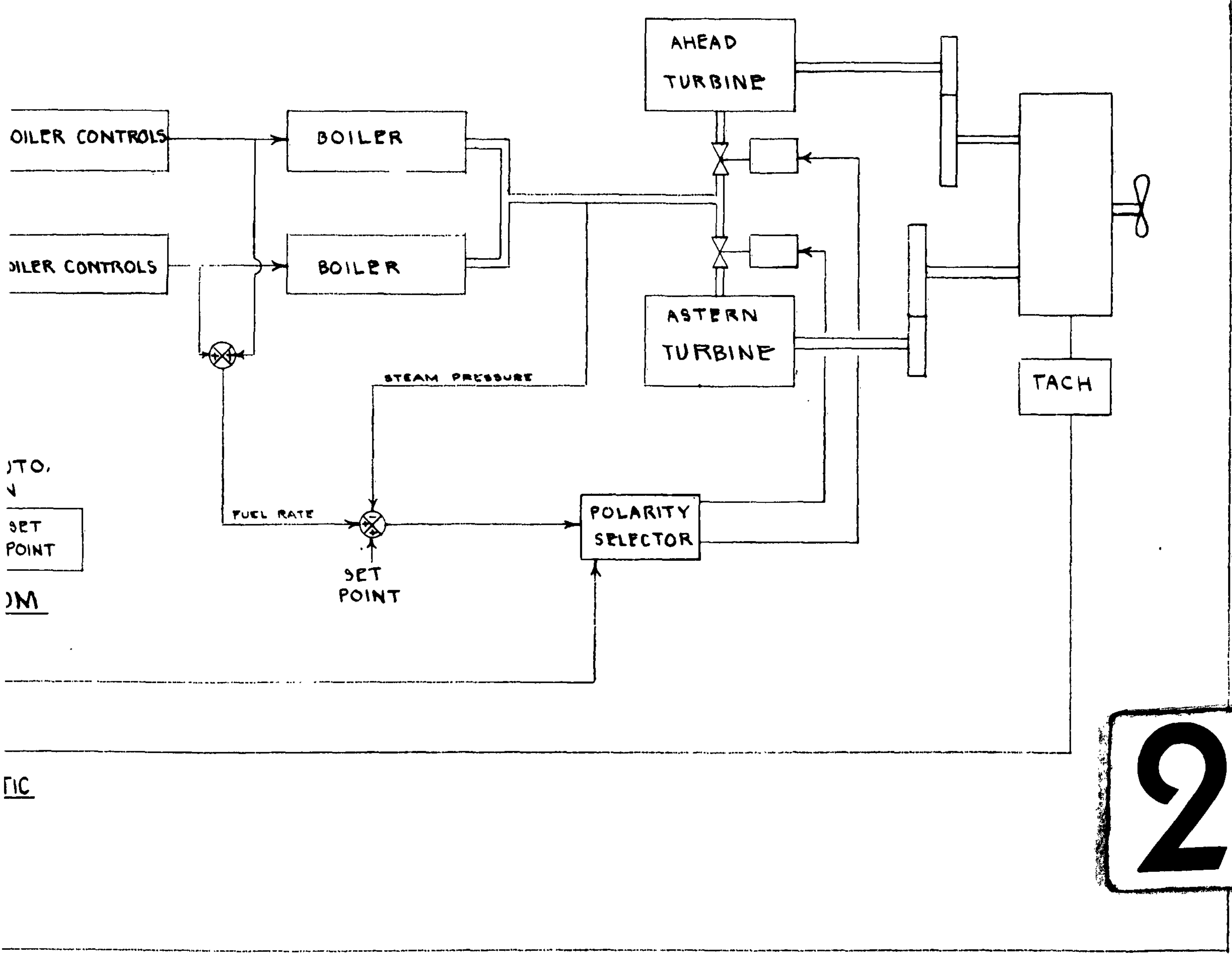

NBTL PROJECT B-511
FULL POWER ASTERN TO FULL POWER AHEAD-22 SECONDS
BOILER PERFORMANCE
PRINTED IN U.S.A.
5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
2

FIG. 13B

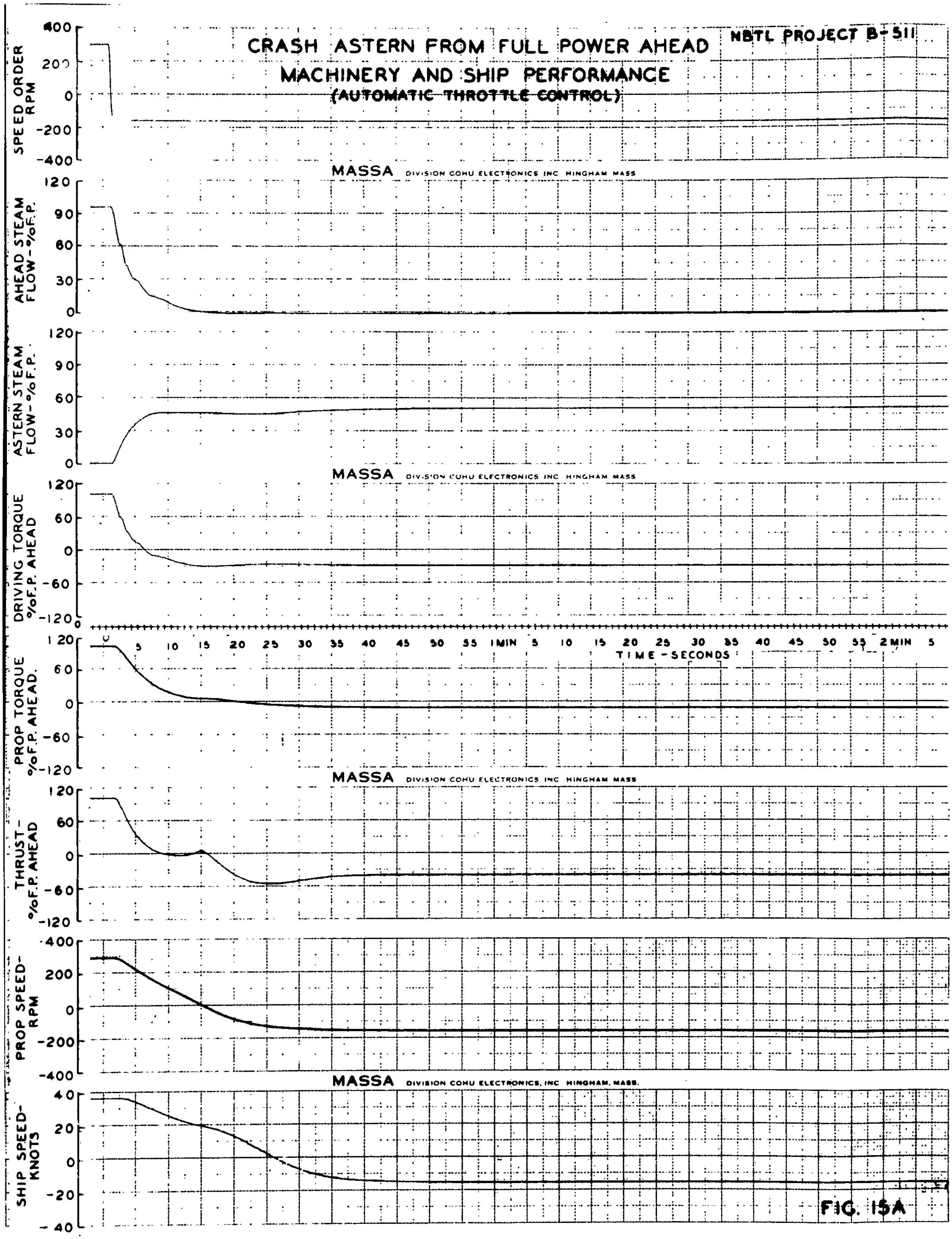
DIAGRAMMATIC ARRANGEM
OF SHAFT SPEED CONTROL S



MATIC ARRANGEMENT
T SPEED CONTROL SYSTEM

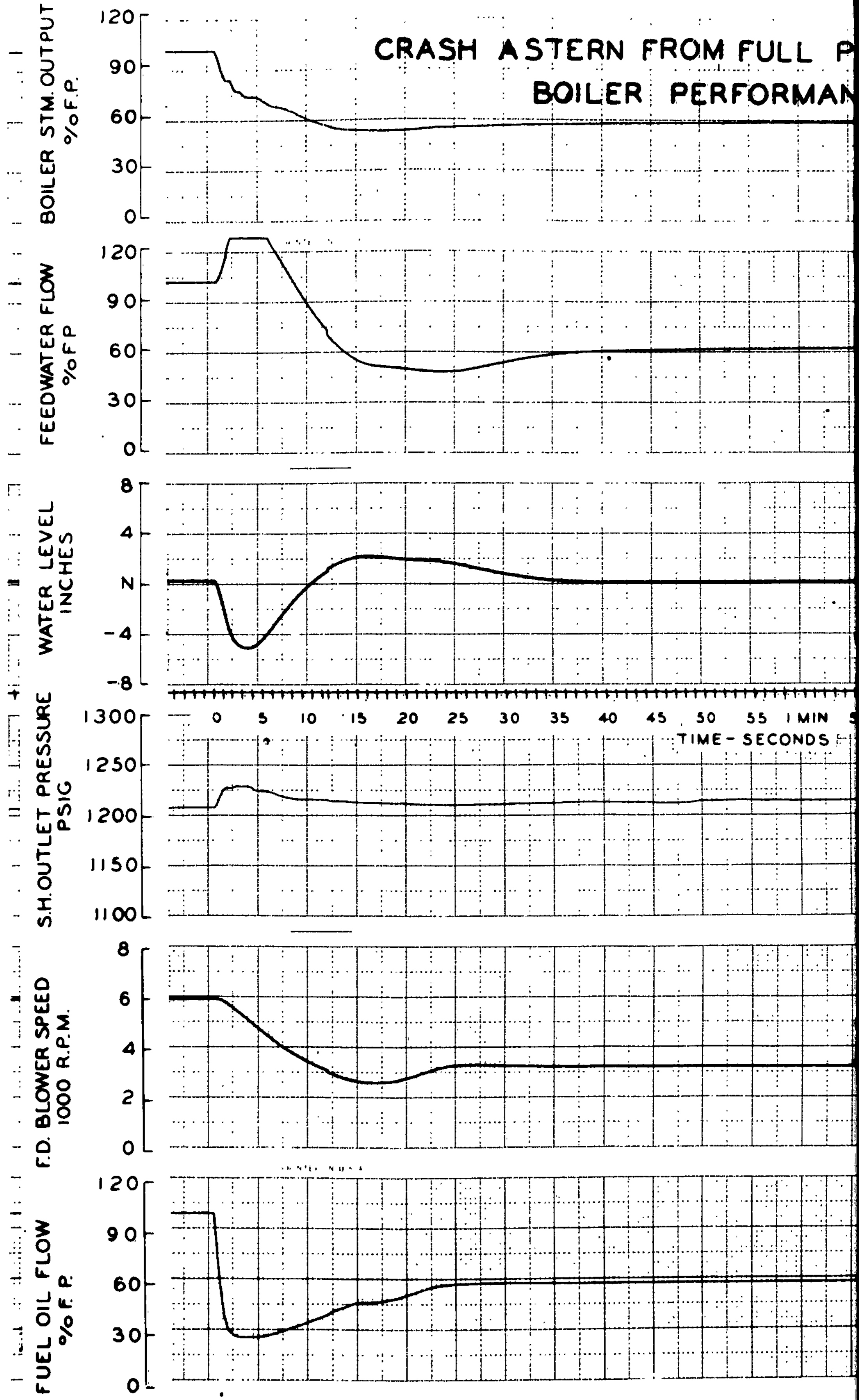


2



CRASH ASTERN FROM FULL POWER AHEAD
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
NBTL PROJECT B-511
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD
THRUST- %F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS

FIG. 15A



CRASH ASTERN FROM FULL P
BOILER PERFORMAN
BOILER STM. OUTPUT %F.P.
FEEDWATER FLOW %F.P.
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %F.P.
TIME - SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN

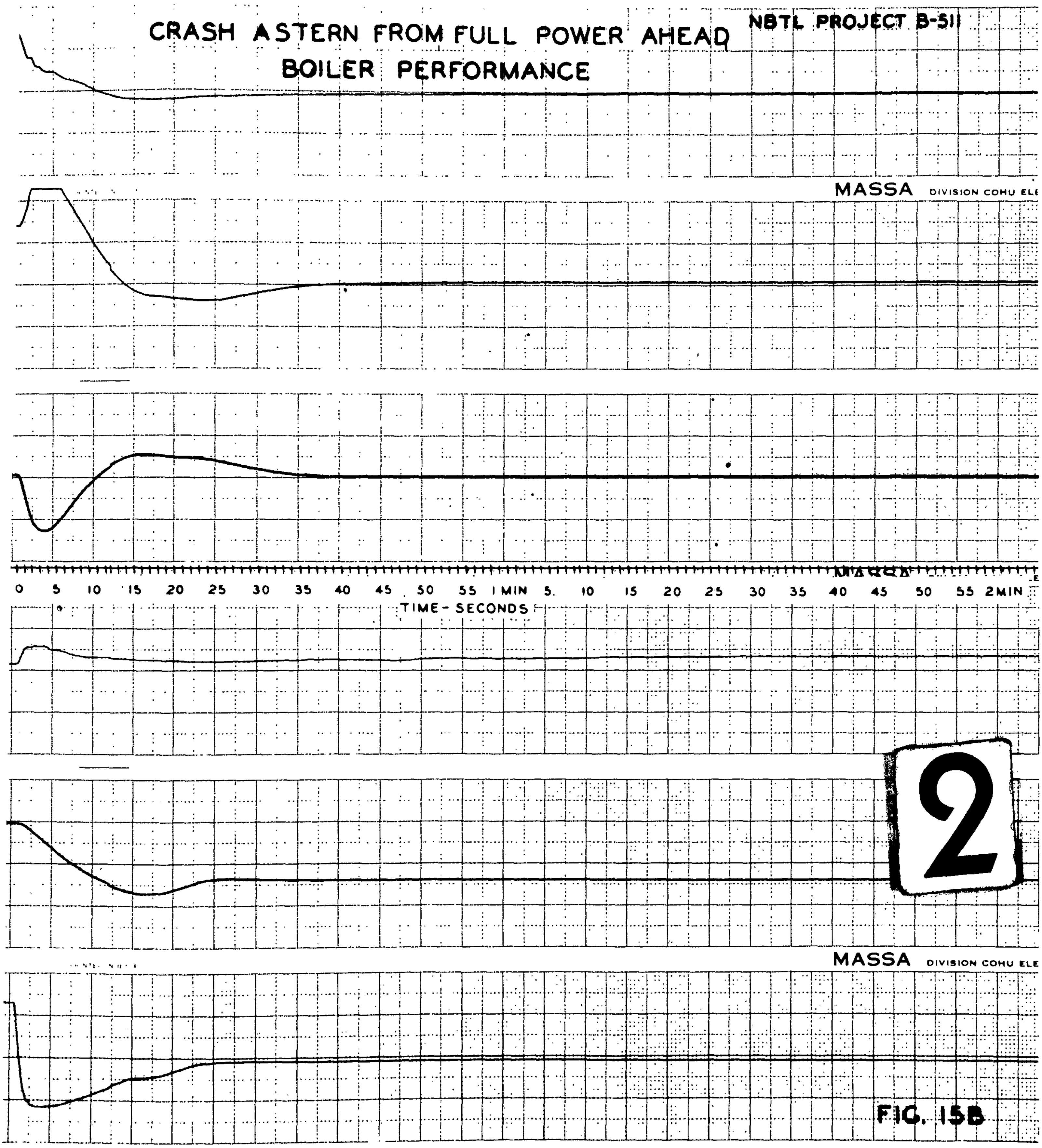
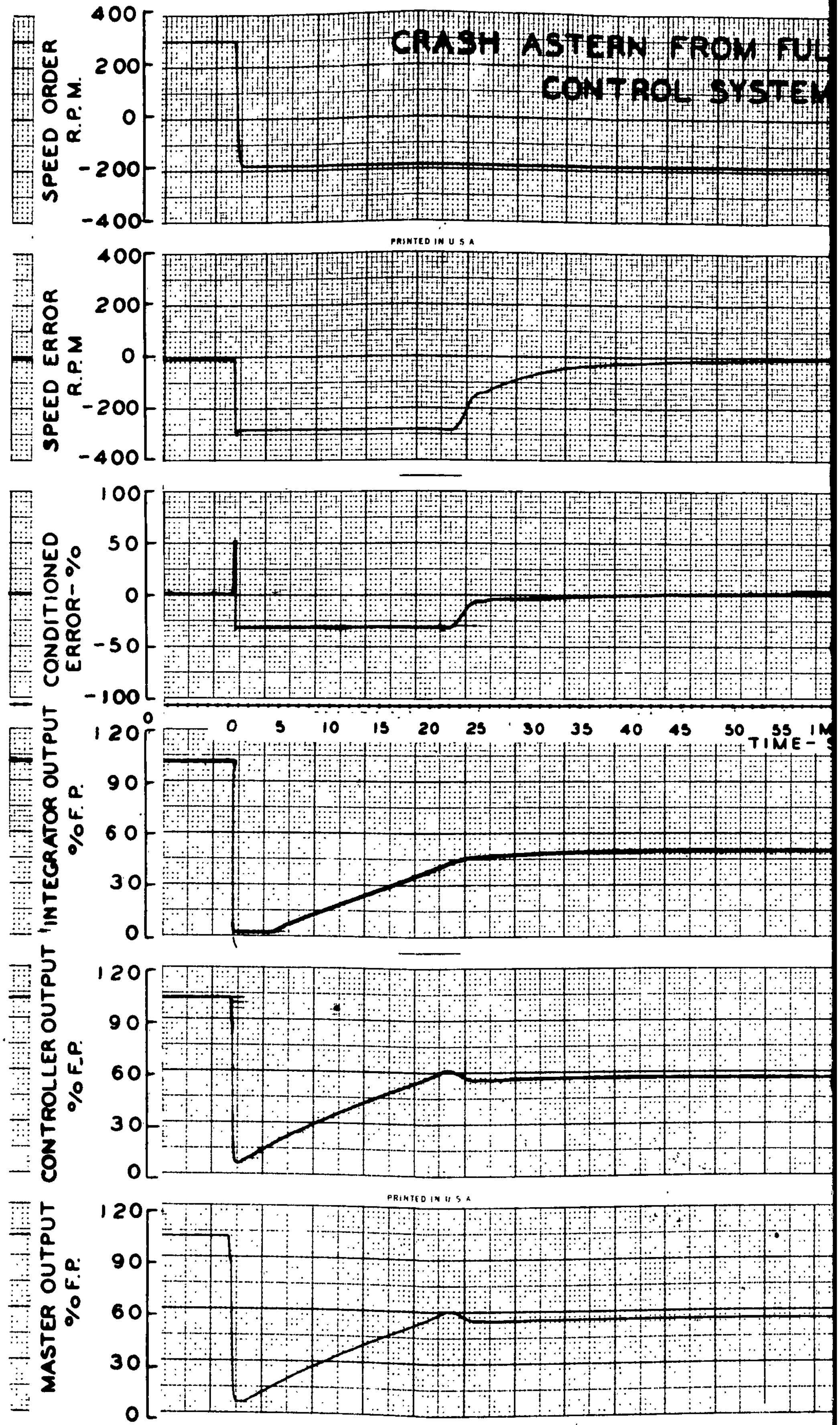

CRASH ASTERN FROM FULL POWER AHEAD
BOILER PERFORMANCE
NBTL PROJECT B-511
MASSA DIVISION COHU ELE
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
MASSA DIVISION COHU ELE
2

FIG. 15B



CRASH ASTERN FROM FUL
CONTROL SYSTEM
SPEED ORDER R.P.M.
400
200
0
-200
-400
PRINTED IN U.S.A.
SPEED ERROR R.P.M.
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55
TIME-
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
PRINTED IN U.S.A.
MASTER OUTPUT %F.P.
120
90
60
30
0

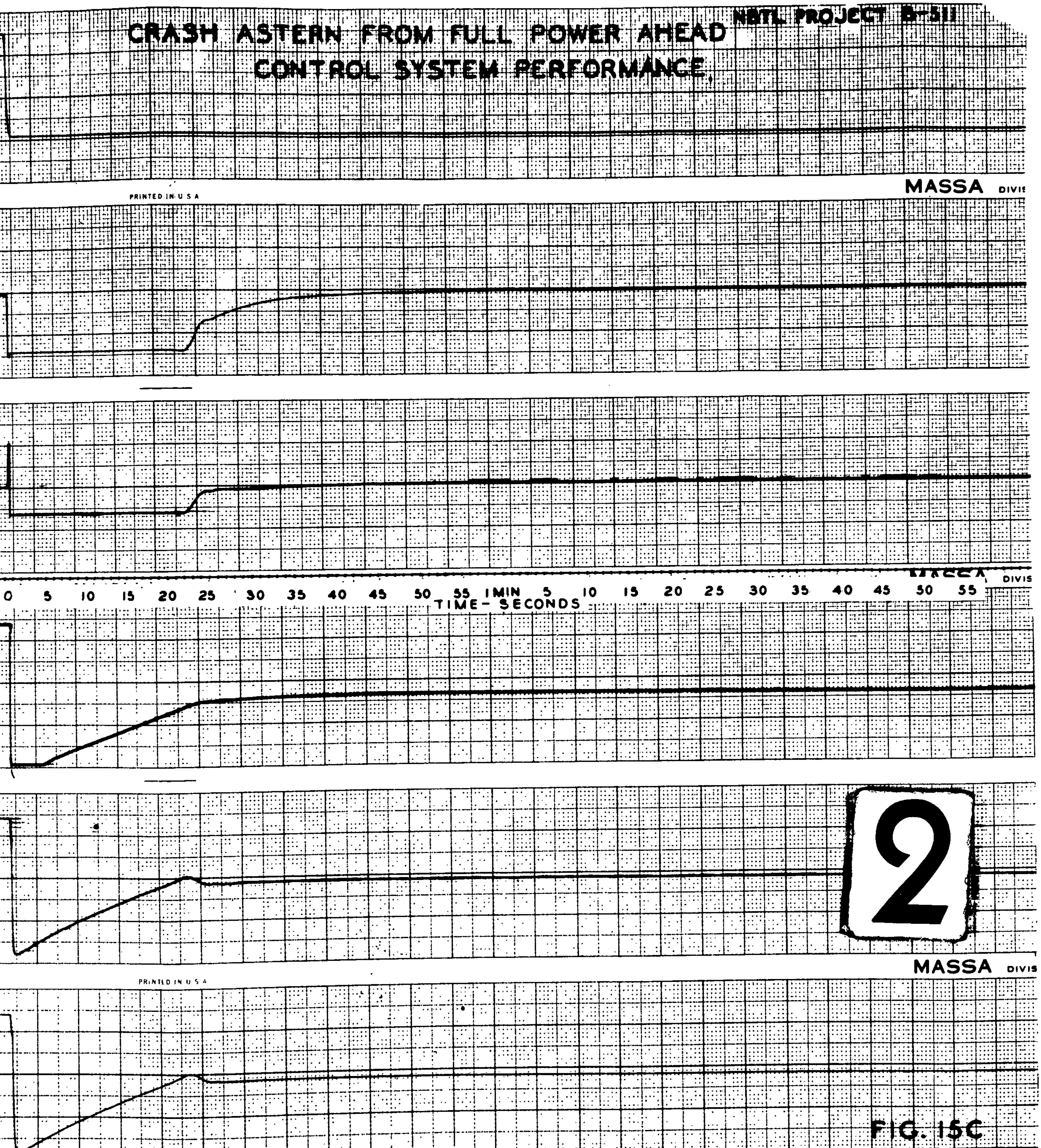
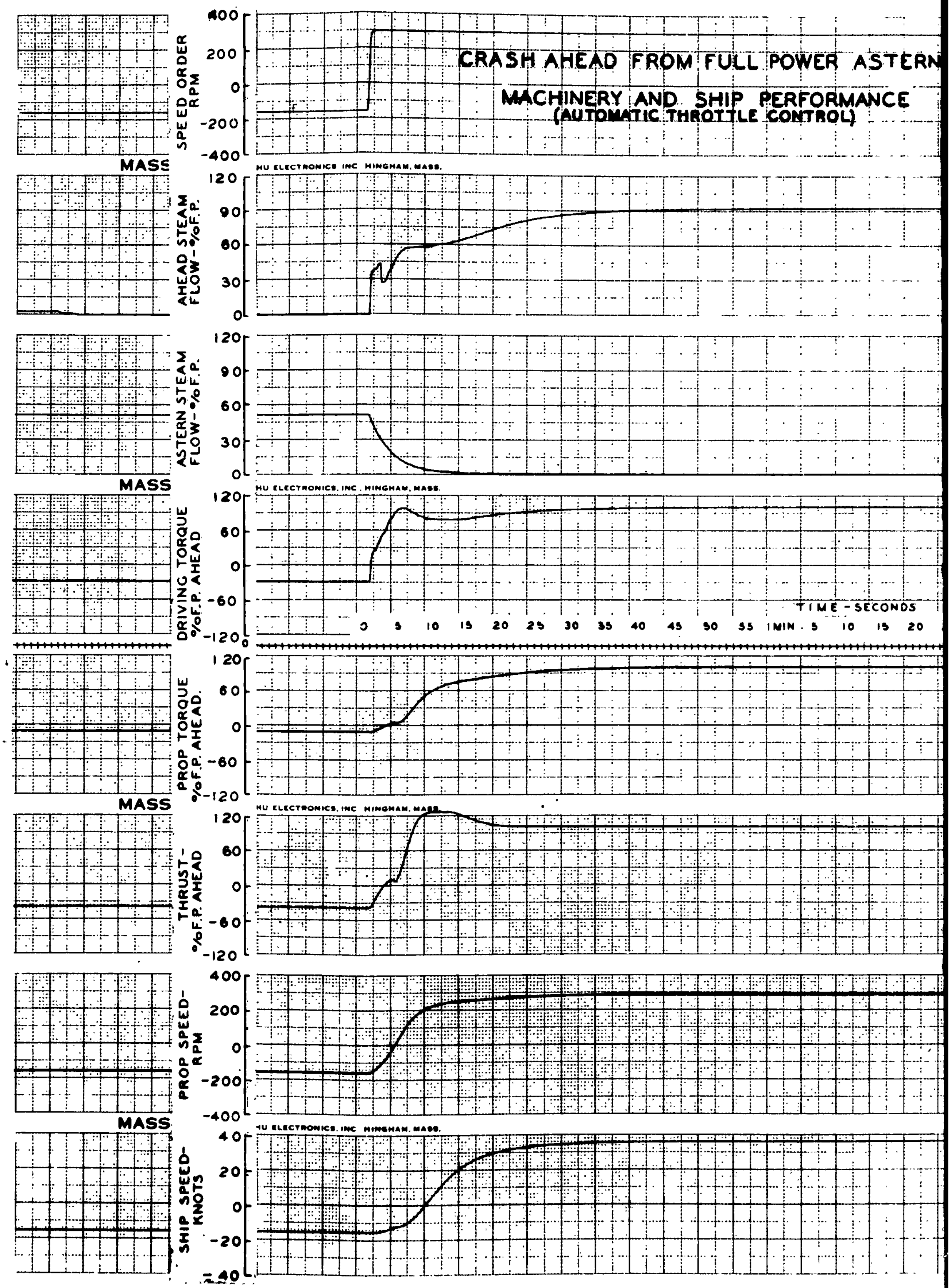

CRASH ASTERN FROM FULL POWER AHEAD
CONTROL SYSTEM PERFORMANCE
NBTL PROJECT B-511
MASSA DIVIS
PRINTED IN U.S.A.
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55
TIME - SECONDS
MASSA DIVIS
2
MASSA DIVIS
PRINTED IN U.S.A.

FIG. 15C


CRASH AHEAD FROM FULL POWER ASTERN
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%of F.P.
ASTERN STEAM FLOW-%of F.P.
DRIVING TORQUE %of F.P. AHEAD
PROP TORQUE %of F.P. AHEAD.
THRUST- %of F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
TIME - SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN. 5 10 15 20
MASS
HU ELECTRONICS INC HINGHAM, MASS.

1

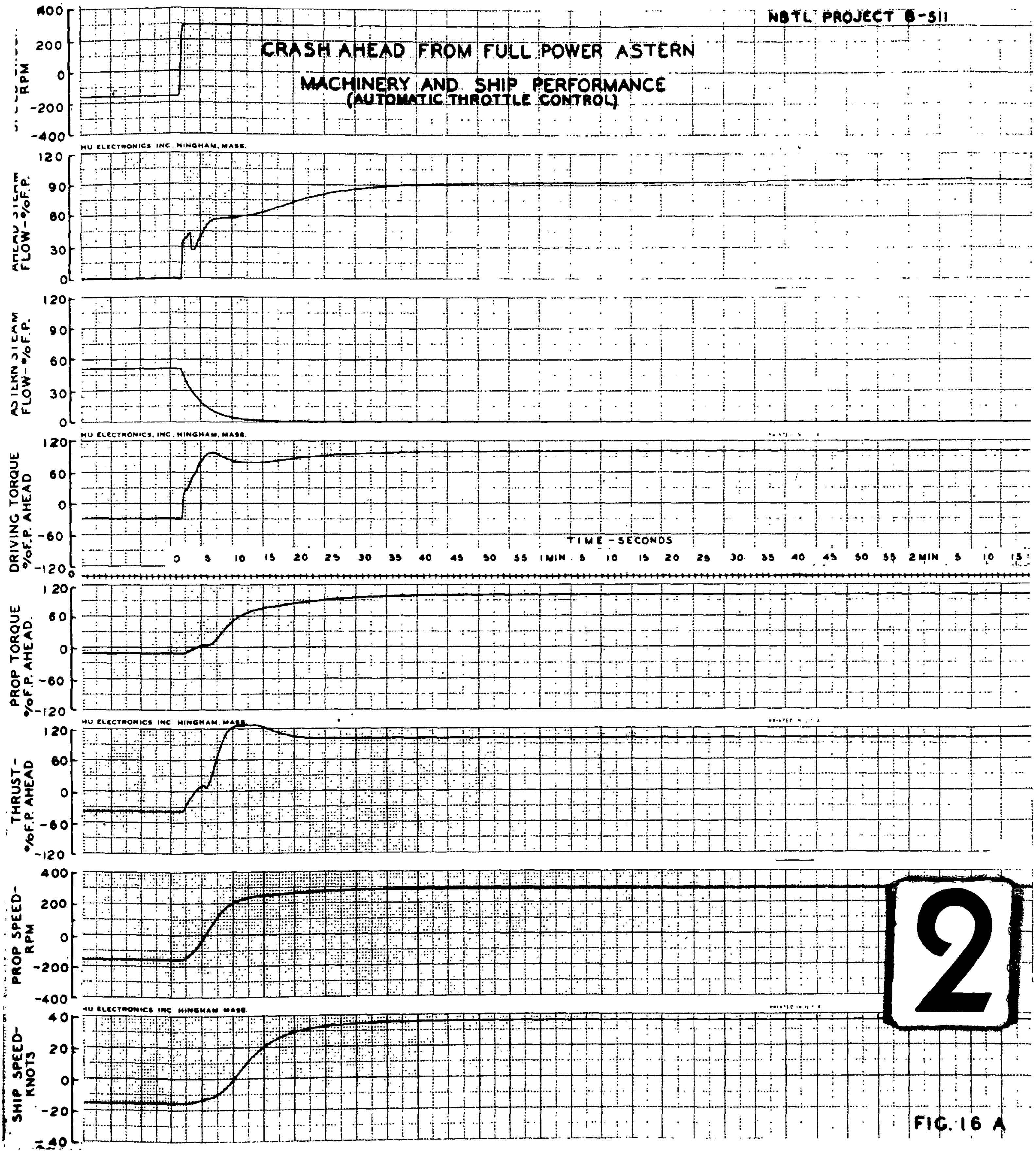
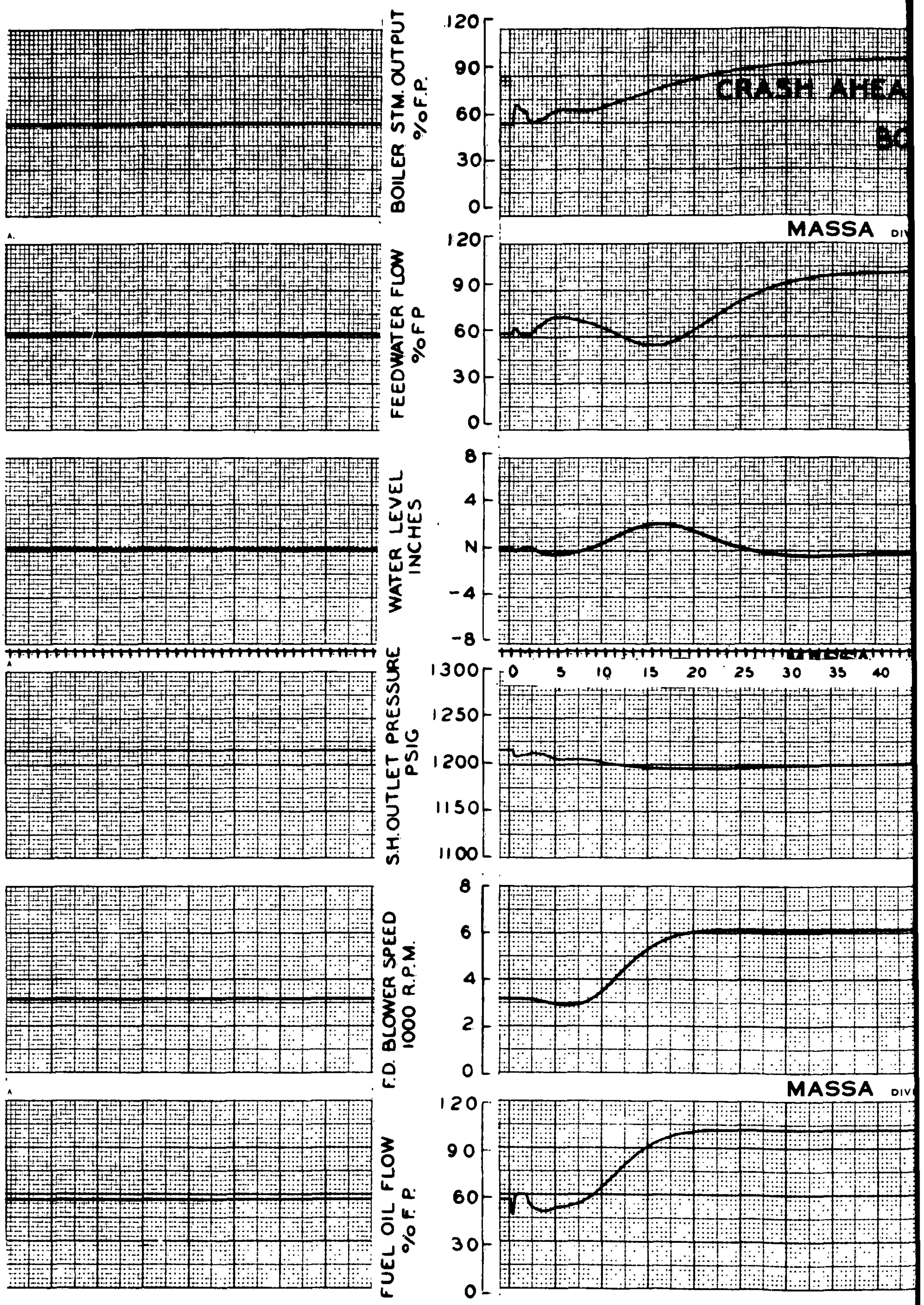

NBTL PROJECT B-511
CRASH AHEAD FROM FULL POWER ASTERN
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %of F.P. AHEAD
TIME - SECONDS
PROP TORQUE %of F.P. AHEAD
THRUST- %of F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
2

FIG. 16 A


BOILER STM. OUTPUT %F.P.
FEEDWATER FLOW %F.P
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %F.P.
MASSA
MASSA
0 5 10 15 20 25 30 35 40
120 90 60 30 0
8 4 N -4 -8
1300 1250 1200 1150 1100
8 6 4 2 0

1

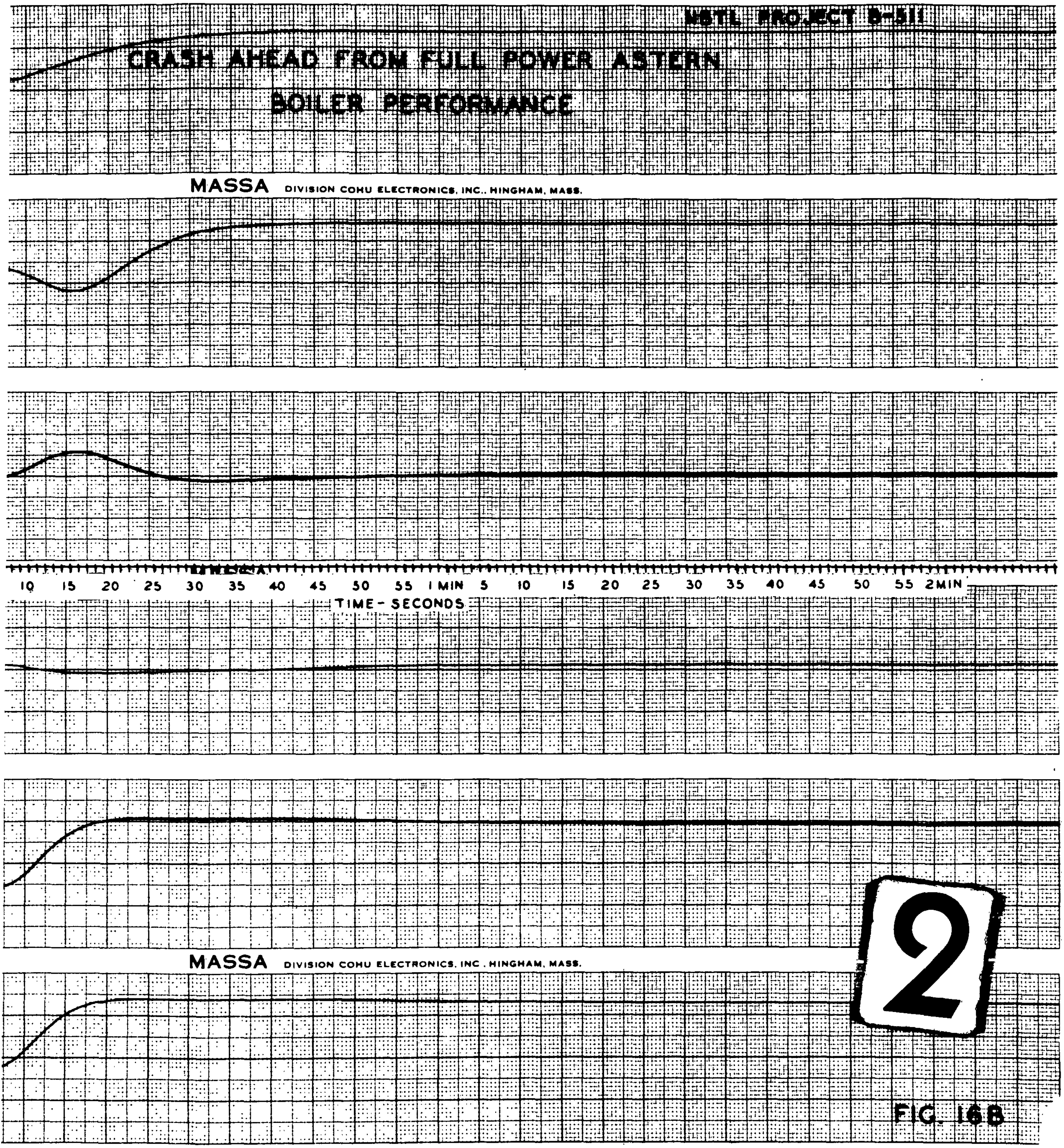
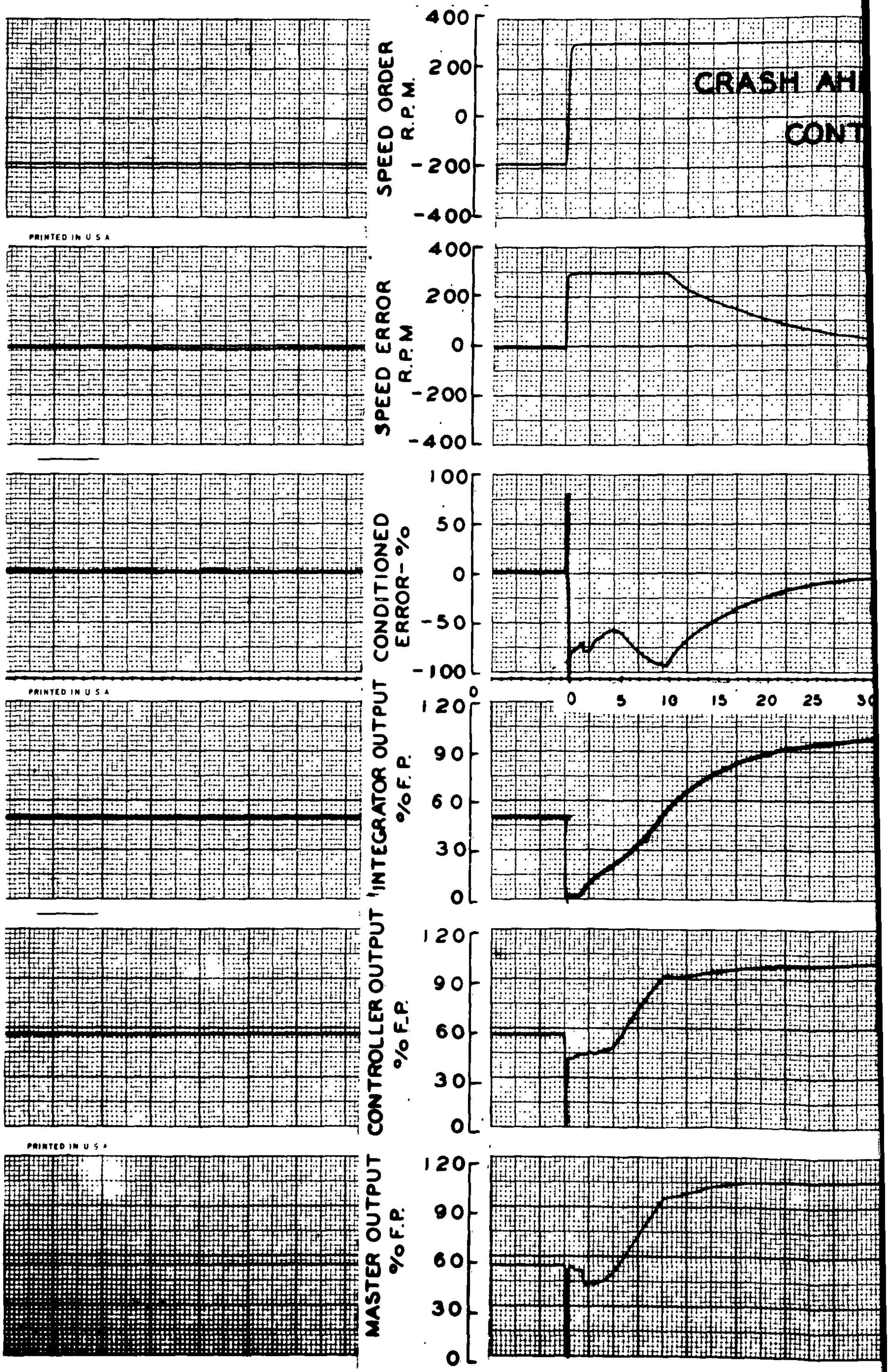
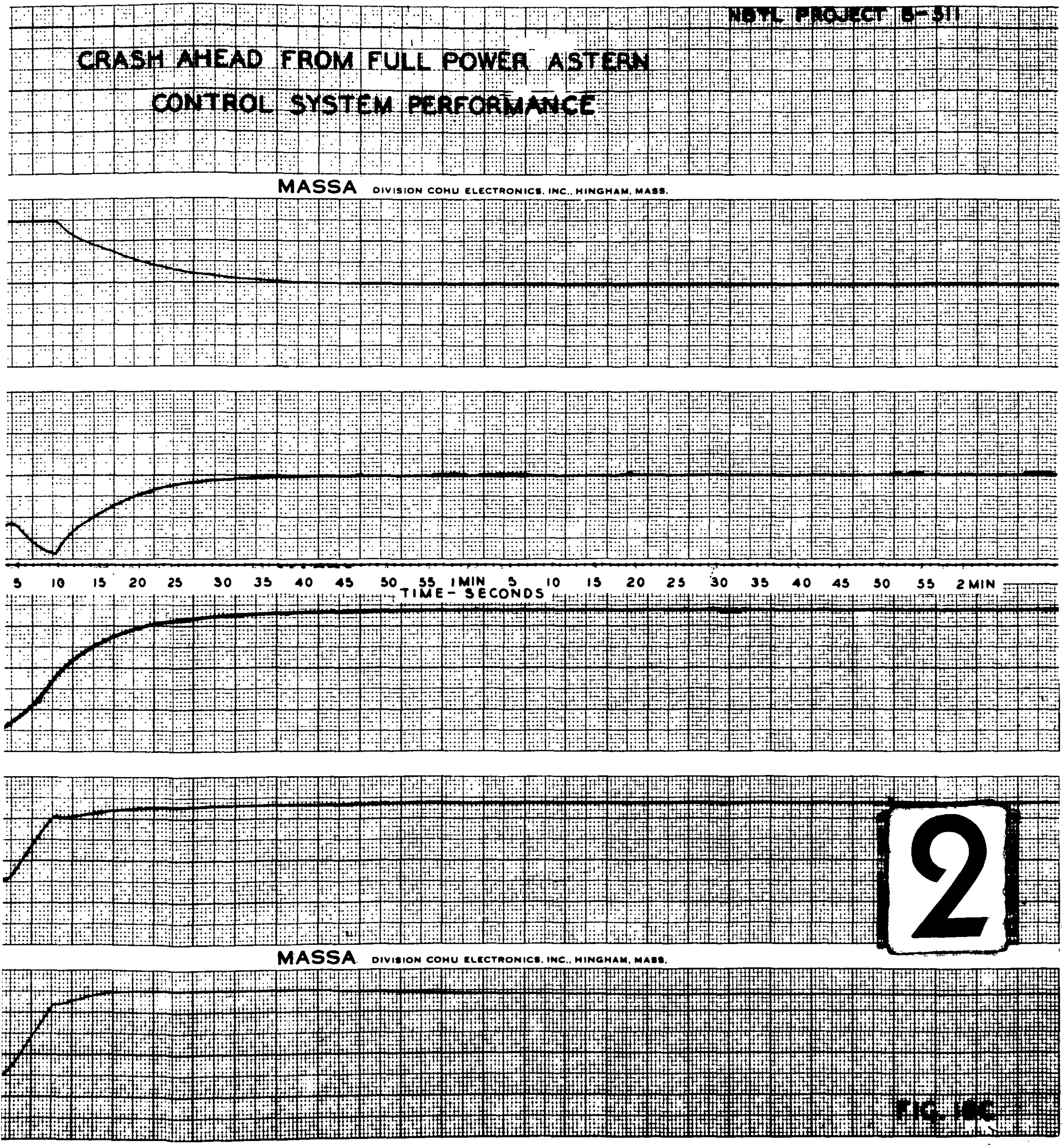

NSTL PROJECT B-511
CRASH AHEAD FROM FULL POWER ASTERN
BOILER PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
2

FIG. 16B


CRASH AH
CONT
SPEED ORDER R.P.M.
400
200
0
-200
-400
PRINTED IN U S A
SPEED ERROR R.P.M.
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
PRINTED IN U S A
0 5 10 15 20 25
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
PRINTED IN U S A
MASTER OUTPUT %F.P.
120
90
60
30
0

1



NBTL PROJECT B-511
CRASH AHEAD FROM FULL POWER ASTERN
CONTROL SYSTEM PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME- SECONDS
2
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.

FIG. 18C

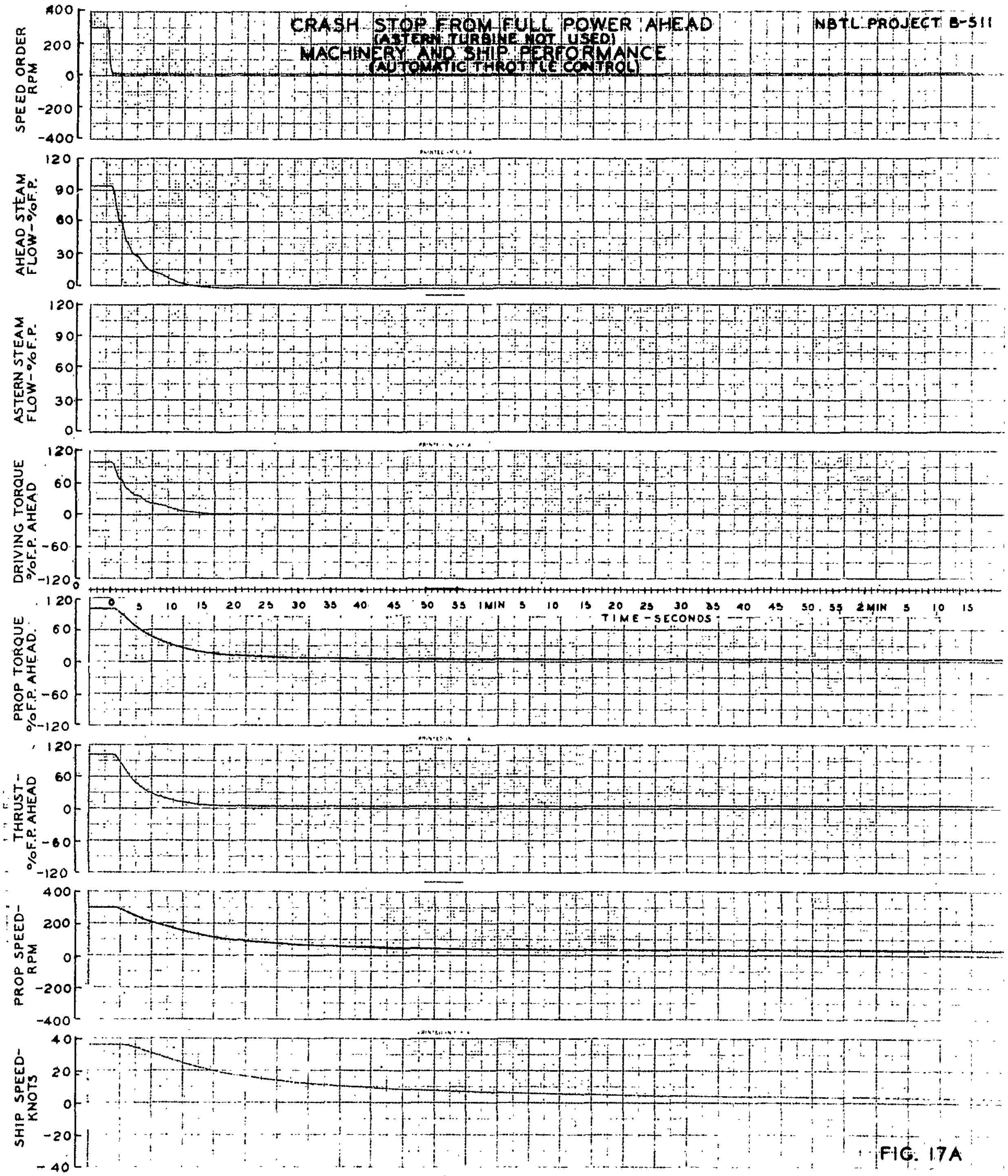
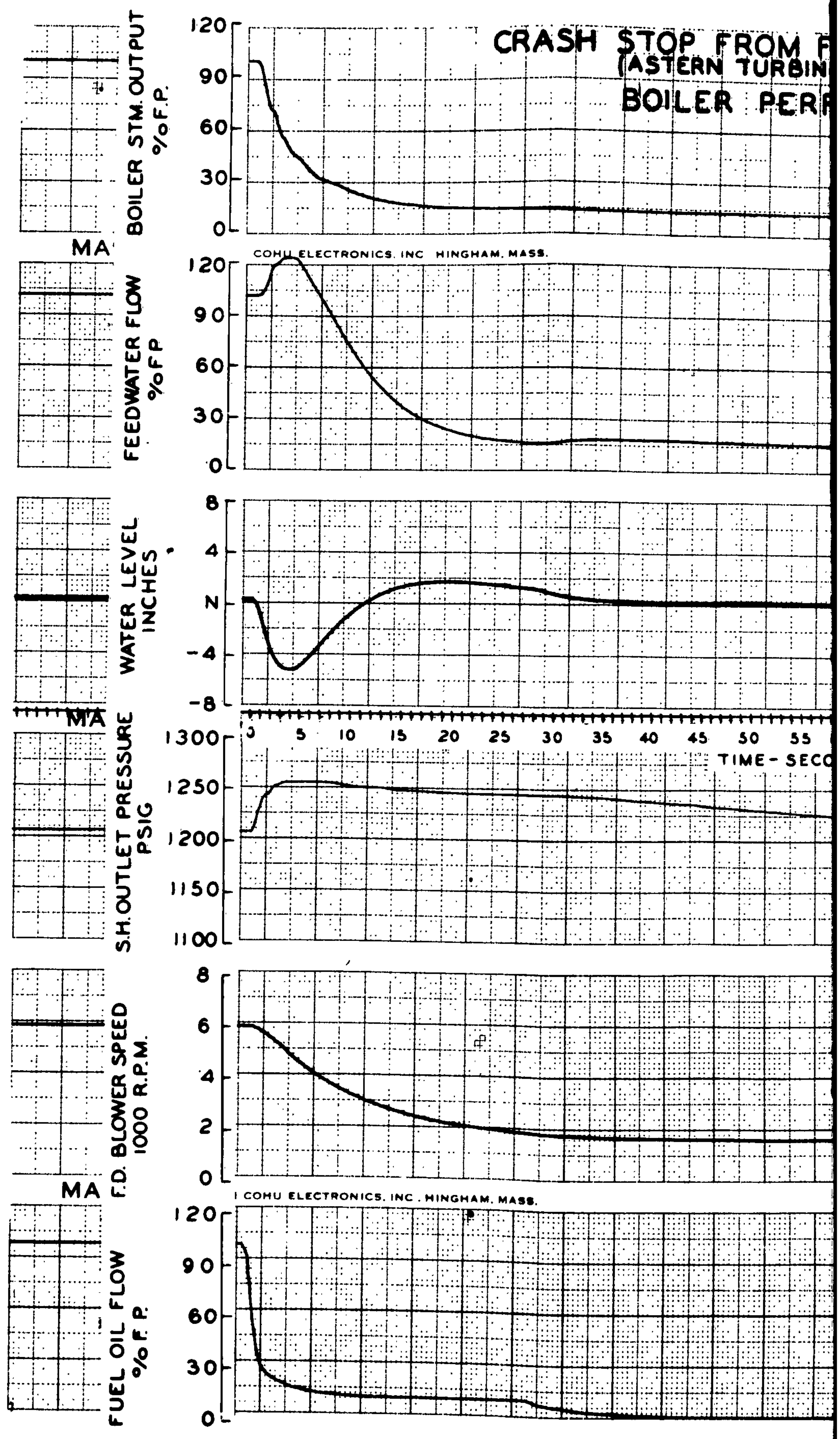
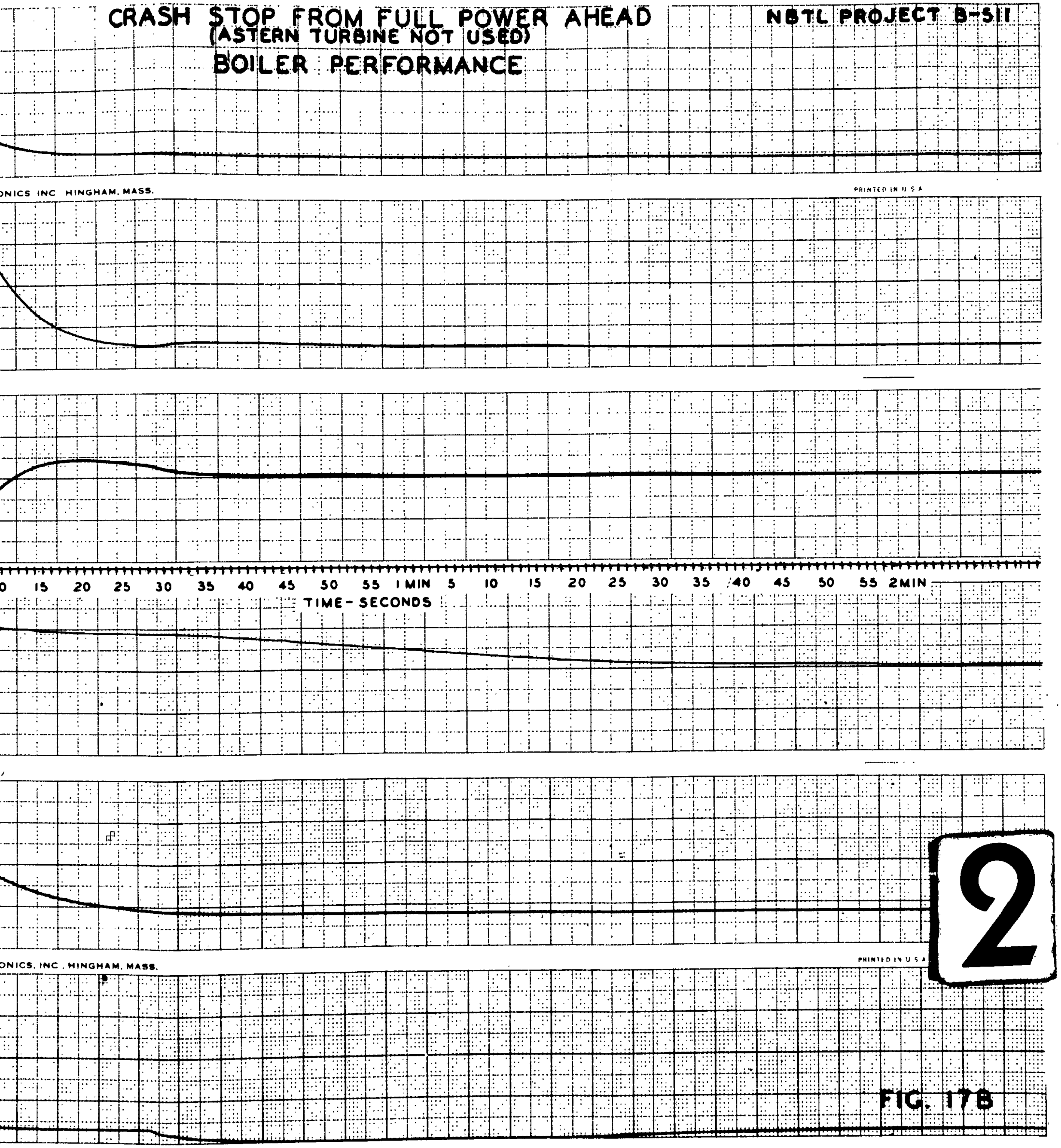
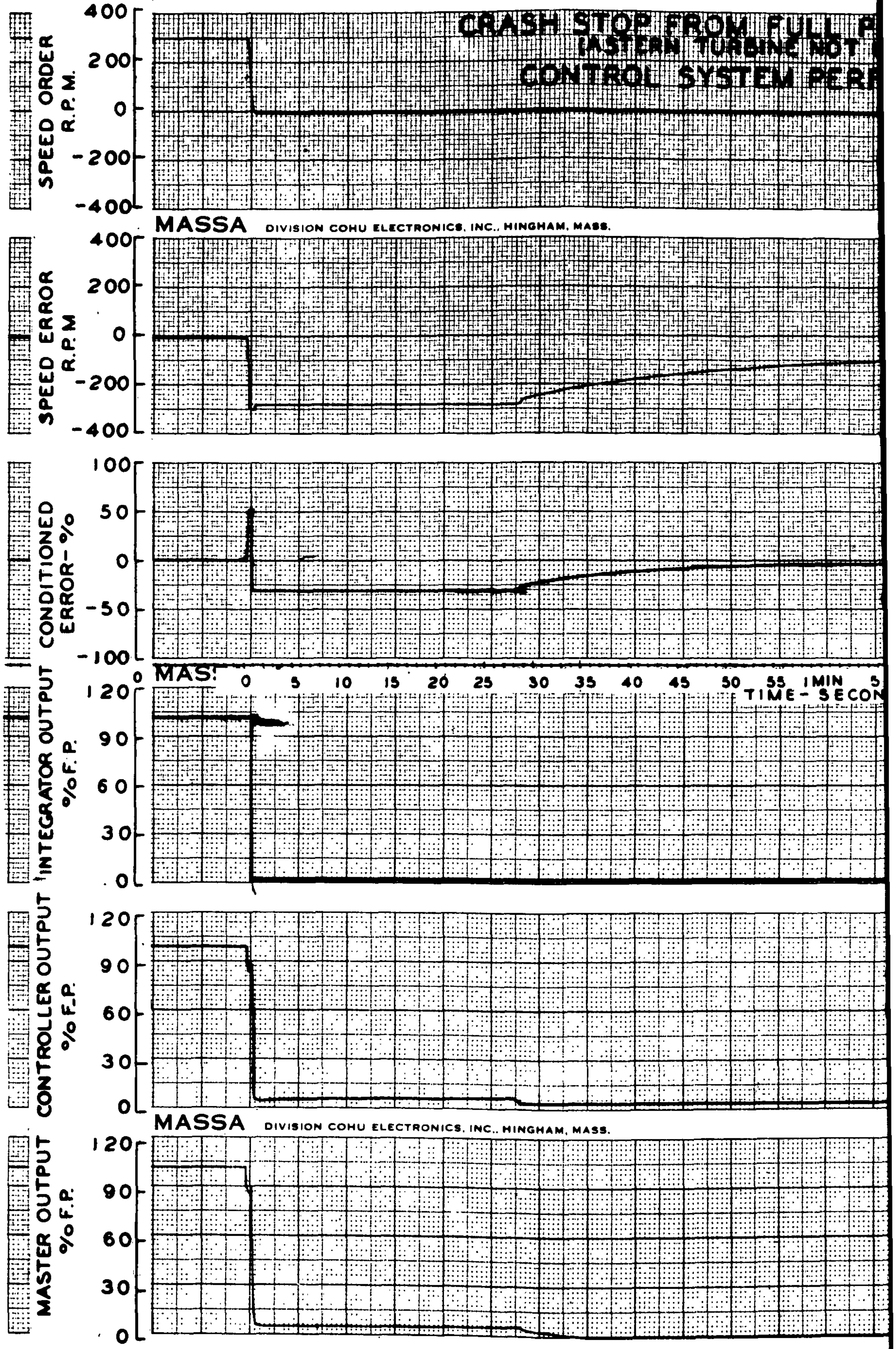

CRASH STOP FROM FULL POWER AHEAD
(ASTERN TURBINE NOT USED)
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
NBTL PROJECT B-511
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD
THRUST-%F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
TIME-SECONDS

FIG. 17A


CRASH STOP FROM F
(ASTERN TURBIN
BOILER PERF
BOILER STM. OUTPUT %oF.P.
MA
COHU ELECTRONICS, INC HINGHAM, MASS.
FEEDWATER FLOW %oFP
WATER LEVEL INCHES
MA
TIME-SECO
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
MA
COHU ELECTRONICS, INC. HINGHAM, MASS.
FUEL OIL FLOW %o F. P.

1


CRASH STOP FROM FULL POWER AHEAD
(ASTERN TURBINE NOT USED)
BOILER PERFORMANCE
NBTL PROJECT B-511
ONICS INC HINGHAM, MASS.
PRINTED IN U.S.A.
0 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
ONICS, INC. HINGHAM, MASS.
PRINTED IN U.S.A.
2
FIG. 17B


CRASH STOP FROM FULL
CONTROL SYSTEM
SPEED ORDER R.P.M.
400
200
0
-200
-400
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
SPEED ERROR R.P.M
CONDITIONED ERROR-%
100
50
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55 1MIN
TIME-
INTEGRATOR OUTPUT %F.P.
120
90
60
30
CONTROLLER OUTPUT %F.P.
MASTER OUTPUT %F.P.

1

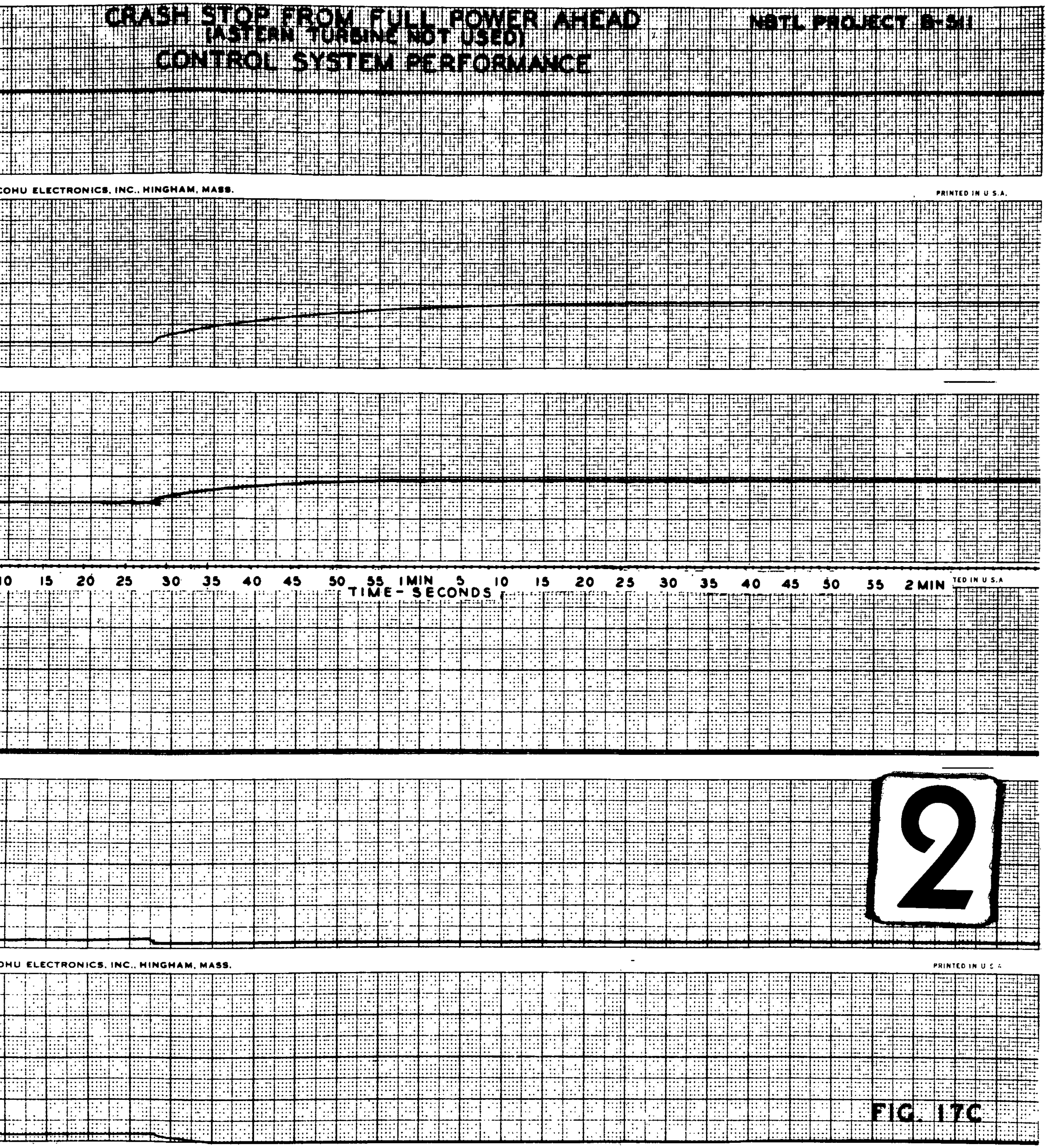

CRASH STOP FROM FULL POWER AHEAD
(ASTERN TURBINE NOT USED)
CONTROL SYSTEM PERFORMANCE
NBTL PROJECT B-511
COHU ELECTRONICS, INC., HINGHAM, MASS.
PRINTED IN U.S.A.
10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME-SECONDS
2
COHU ELECTRONICS, INC., HINGHAM, MASS.
PRINTED IN U.S.A.

FIG. 17C

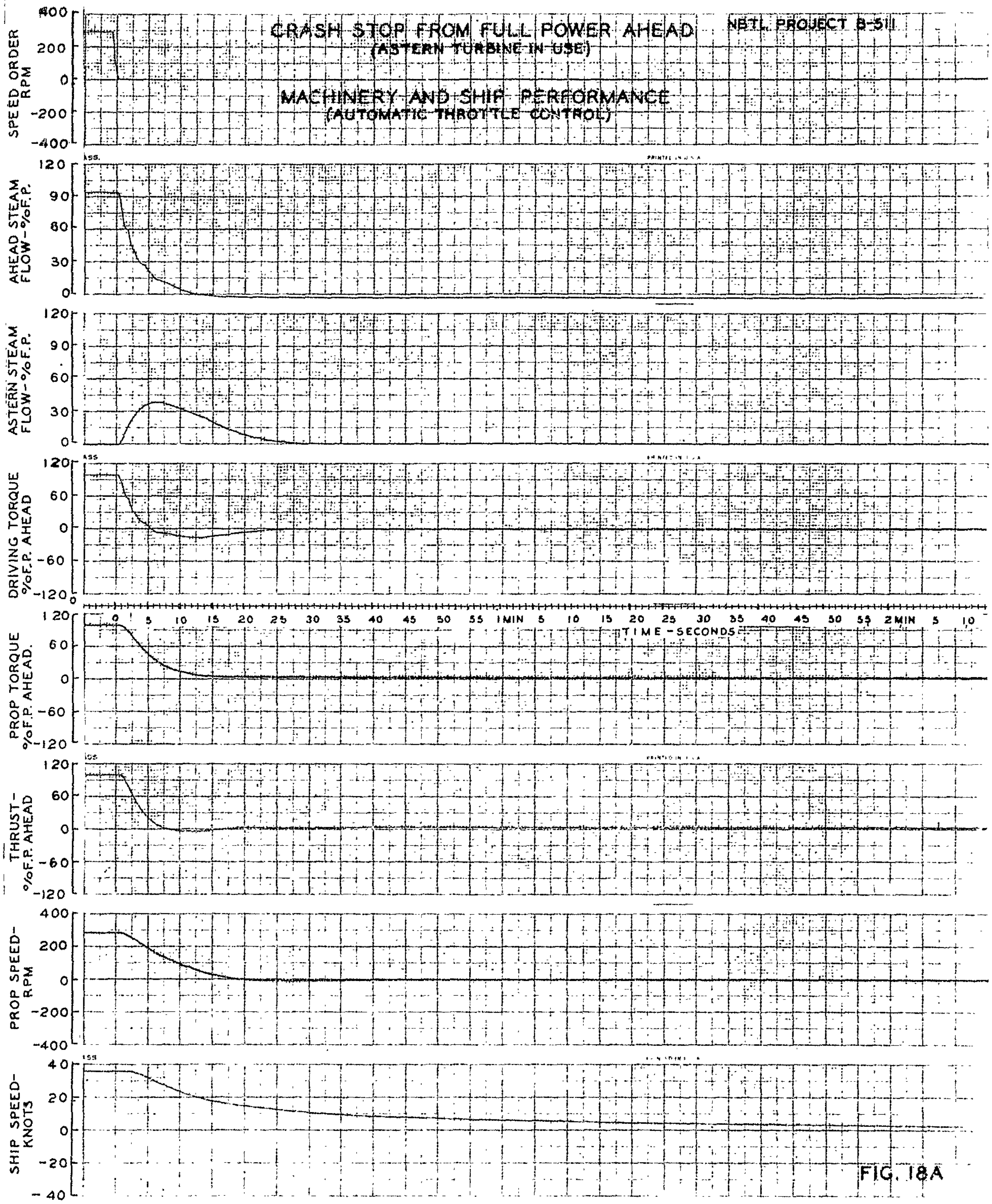
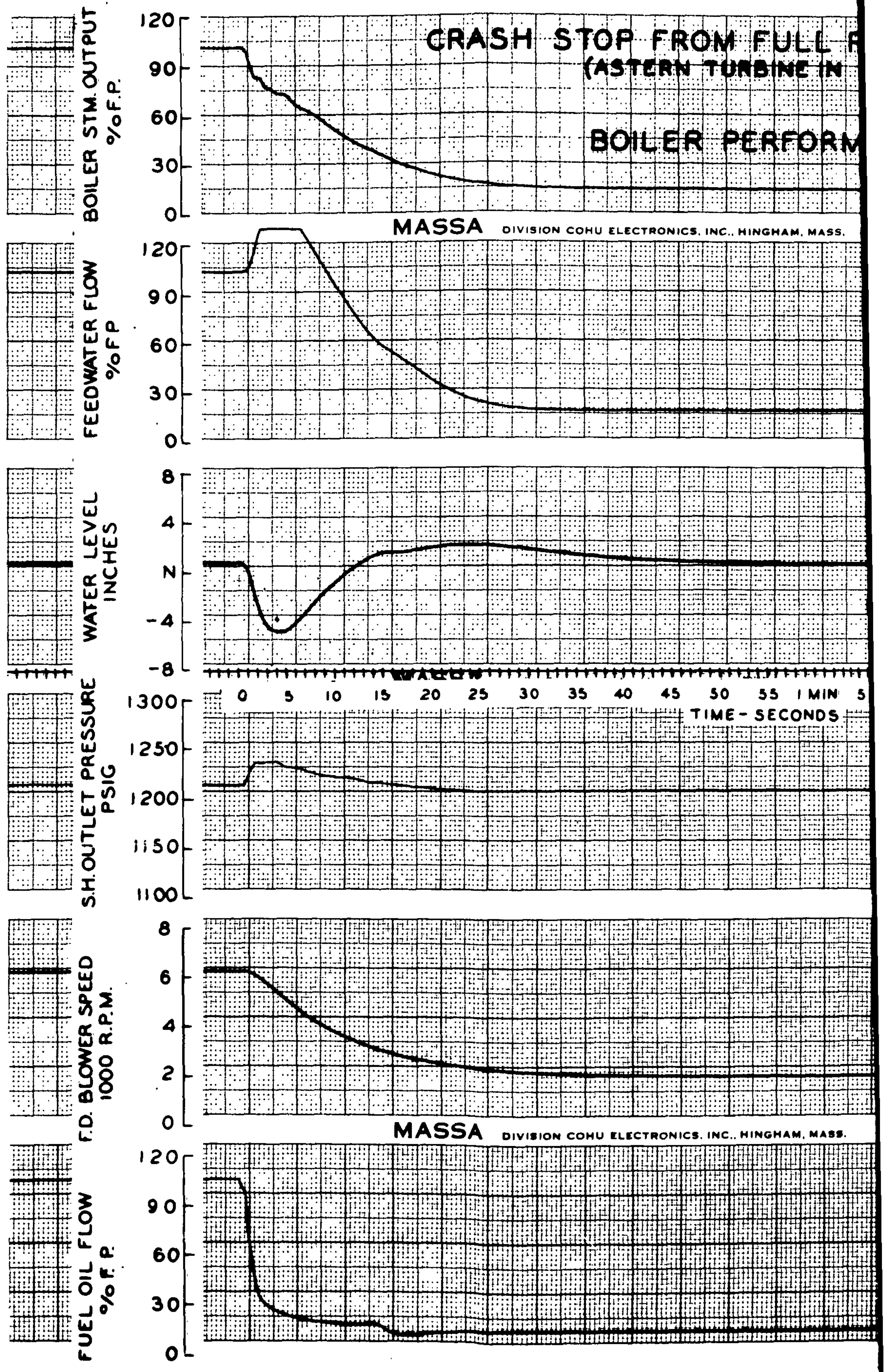

CRASH STOP FROM FULL POWER AHEAD
(ASTERN TURBINE IN USE)
NBTL PROJECT B-511
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-% F.P.
ASTERN STEAM FLOW-% F.P.
DRIVING TORQUE % F.P. AHEAD
PROP TORQUE % F.P. AHEAD.
THRUST- % F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
TIME - SECONDS
1 MIN
2 MIN

FIG. 18A



CRASH STOP FROM FULL
(ASTERN TURBINE IN
BOILER PERFORM
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
BOILER STM. OUTPUT %oF.P.
FEEDWATER FLOW %oFP
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %oF.P.
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.

1

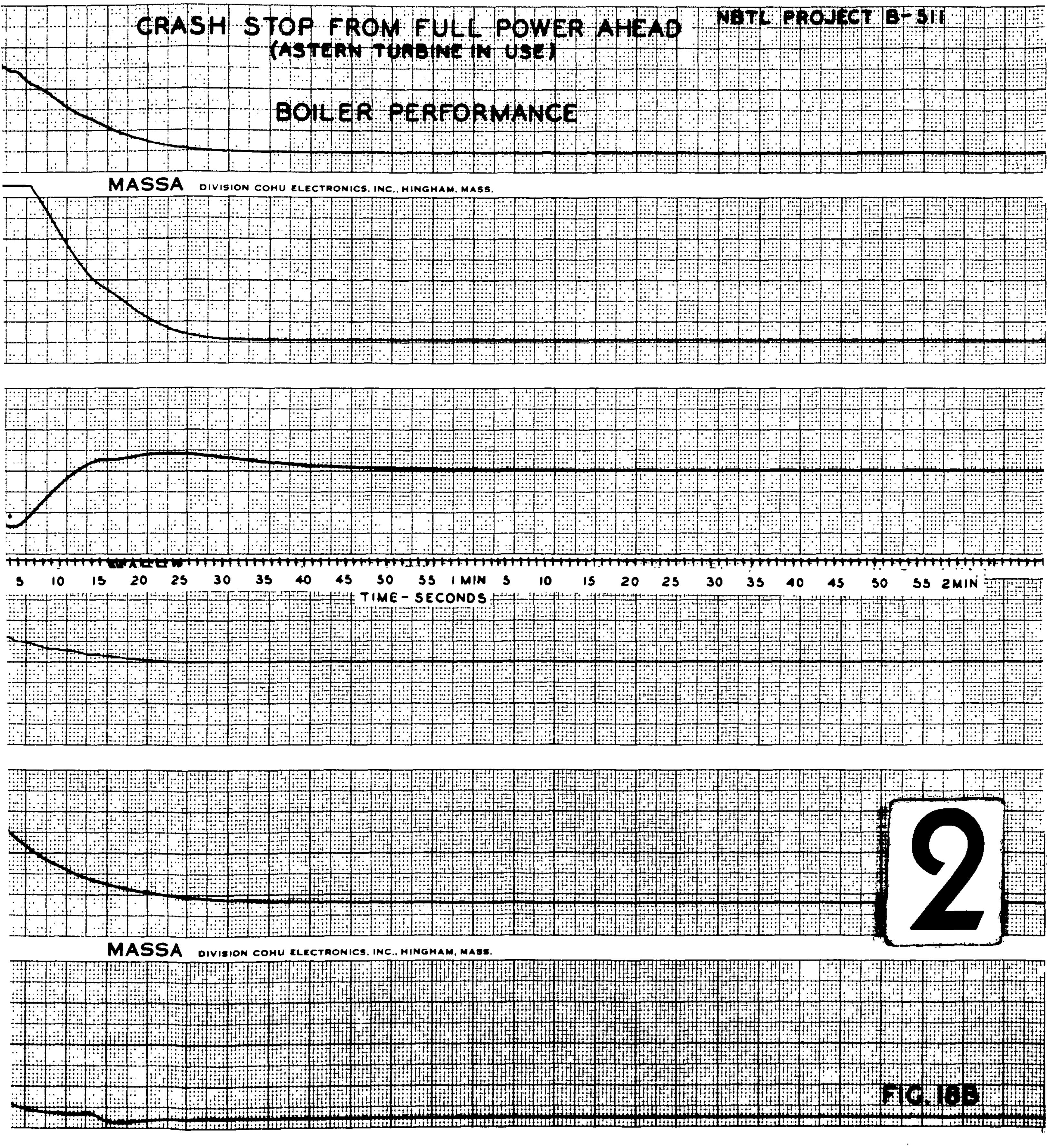
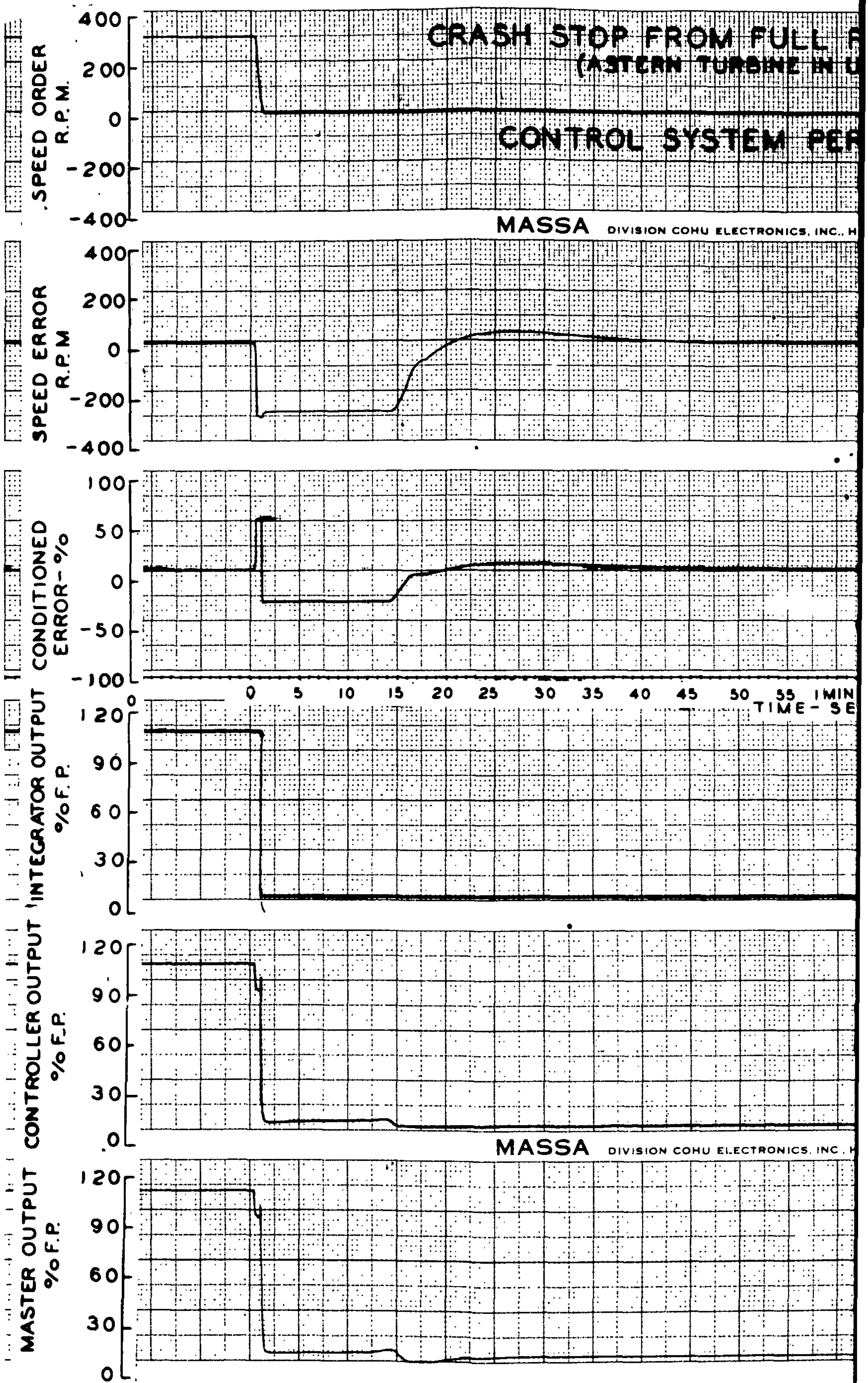

CRASH STOP FROM FULL POWER AHEAD
(ASTERN TURBINE IN USE)
NBTL PROJECT B-511
BOILER PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
2
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.

FIG. 18B



CRASH STOP FROM FULL
(ASTERN TURBINE IN
CONTROL SYSTEM PER
SPEED ORDER R.P.M.
400
200
0
-200
-400
MASSA DIVISION COHU ELECTRONICS, INC.
SPEED ERROR R.P.M
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55 1MIN
TIME-SE
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
MASSA DIVISION COHU ELECTRONICS, INC.
MASTER OUTPUT %F.P.
120
90
60
30
0

1

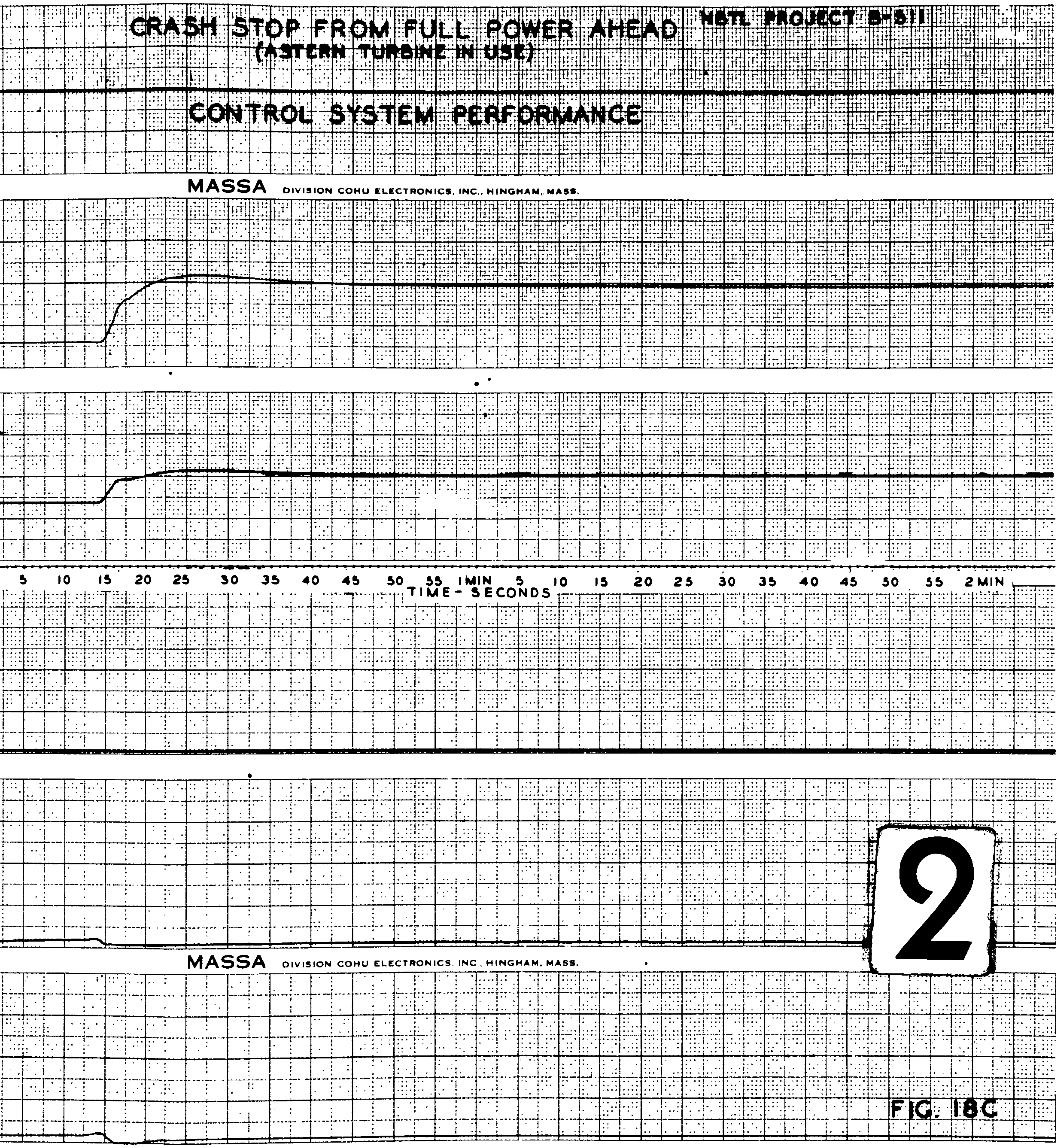
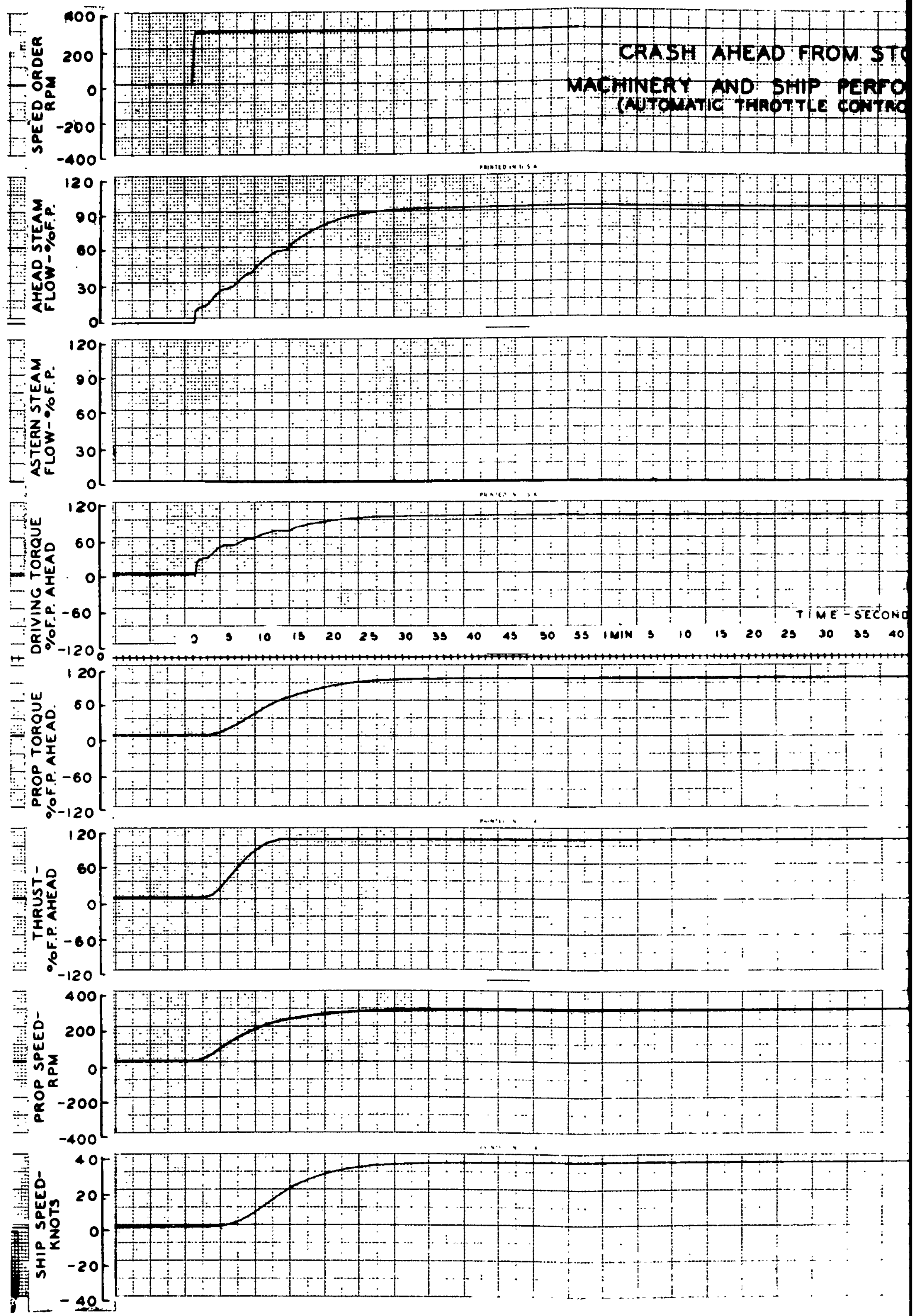
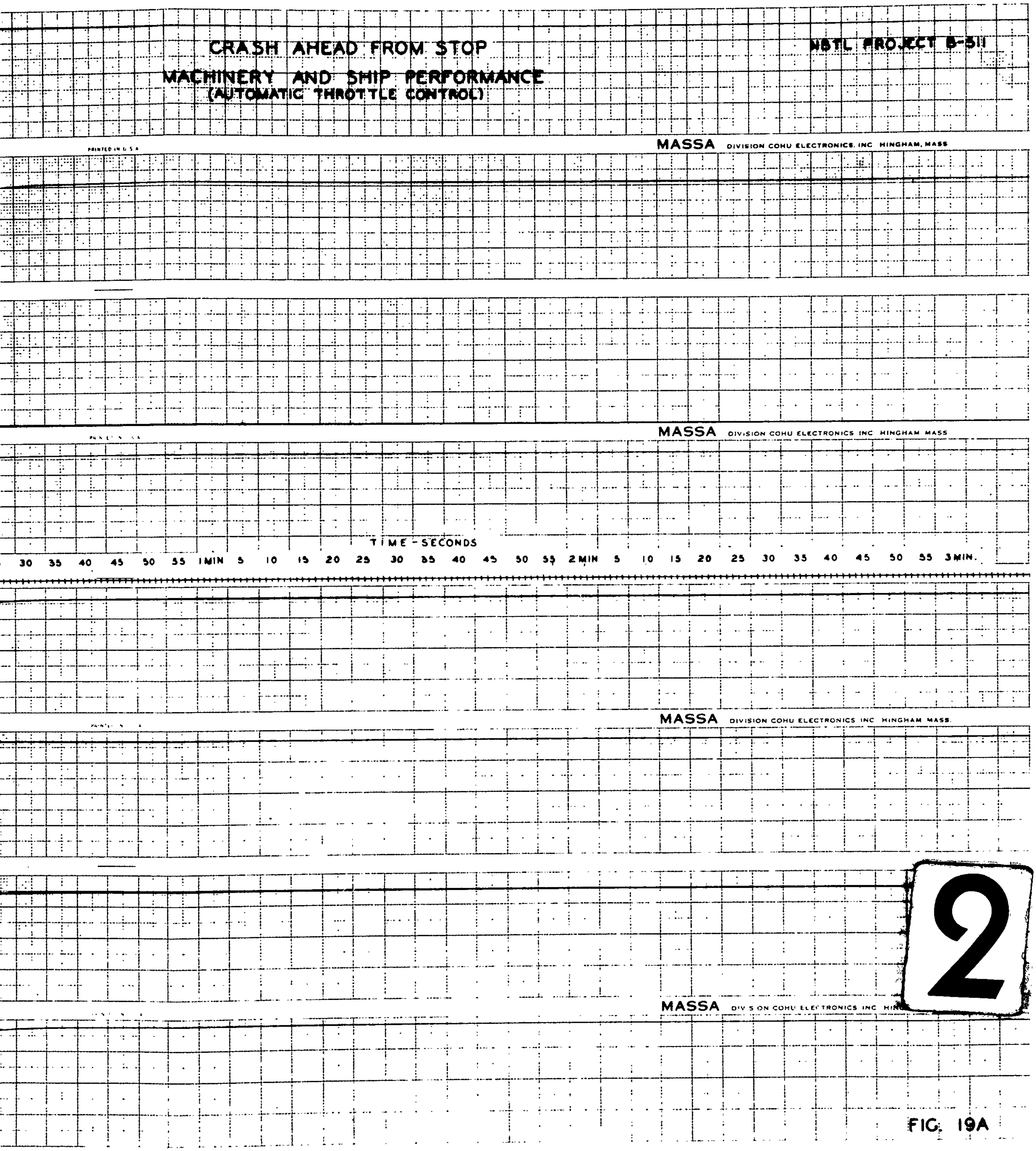

CRASH STOP FROM FULL POWER AHEAD
(ASTERN TURBINE IN USE)
NBTL PROJECT B-511
CONTROL SYSTEM PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME-SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
2

FIG. 18C



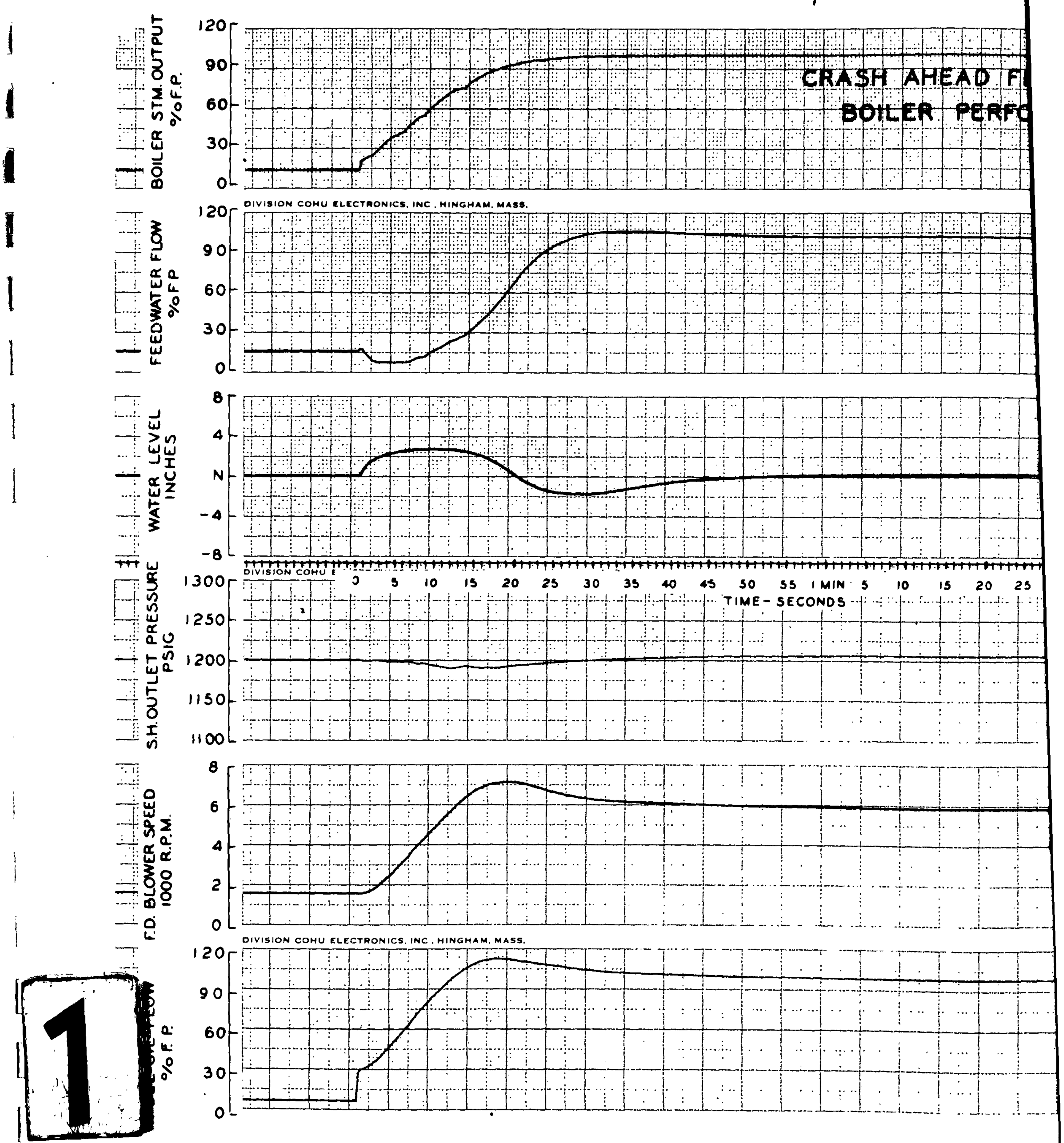
CRASH AHEAD FROM STO
MACHINERY AND SHIP PERFO
(AUTOMATIC THROTTLE CONTRO
SPEED ORDER RPM
AHEAD STEAM FLOW-%of F.P.
ASTERN STEAM FLOW-%of F.P.
DRIVING TORQUE %of F.P. AHEAD
TIME-SECOND
PROP TORQUE %of F.P. AHEAD
THRUST-%of F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS

1



CRASH AHEAD FROM STOP
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
NBTL PROJECT B-511
MASSA DIVISION COHU ELECTRONICS, INC HINGHAM, MASS
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS
TIME - SECONDS
30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN 5 10 15 20 25 30 35 40 45 50 55 3MIN.
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS.
MASSA
2

FIG. 19A



CRASH AHEAD F
BOILER PERFO
BOILER STM. OUTPUT %o F.P.
DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
FEEDWATER FLOW %o F P
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
TIME - SECONDS
F.D. BLOWER SPEED 1000 R.P.M.
%o F.P.
1

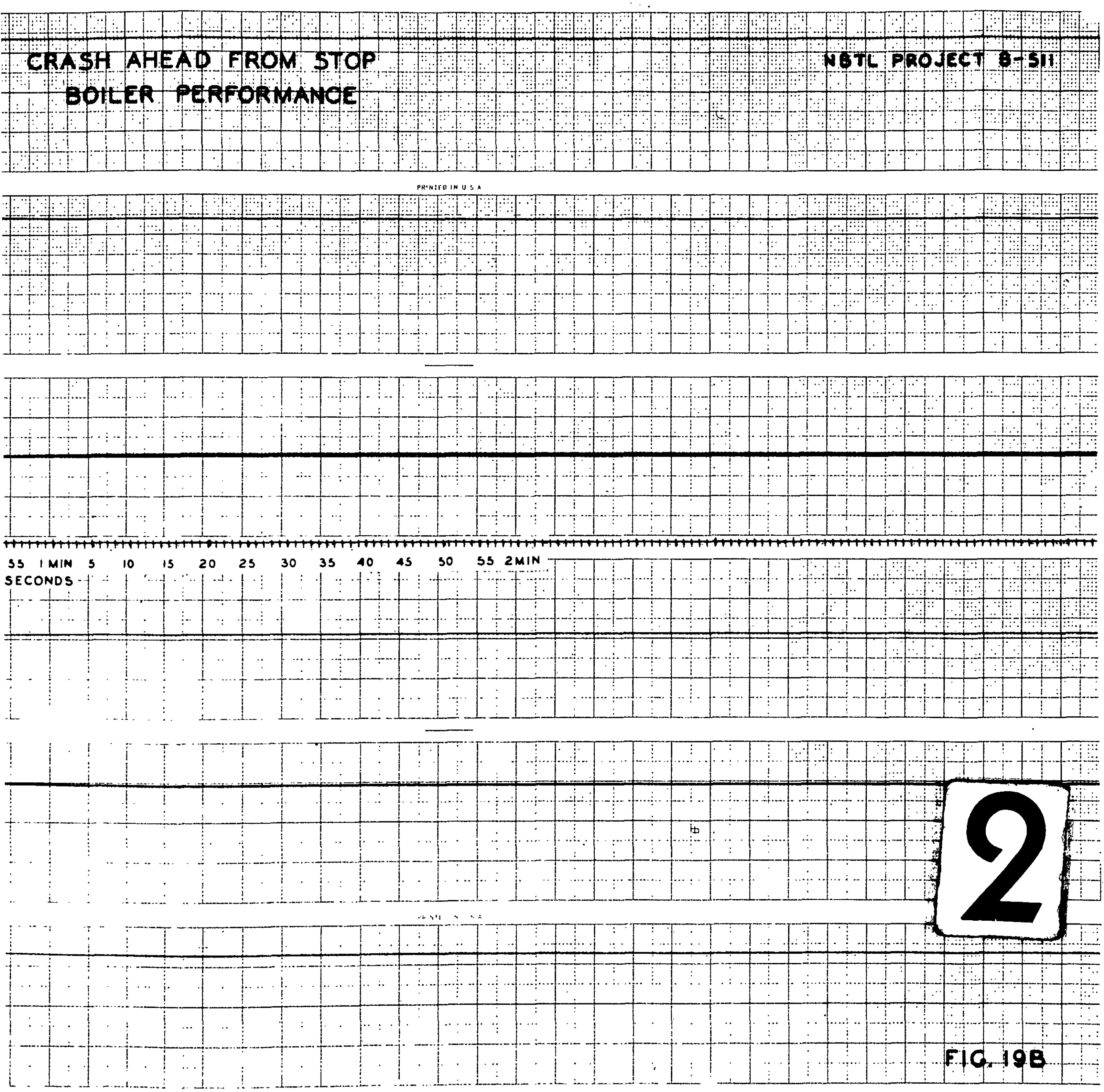
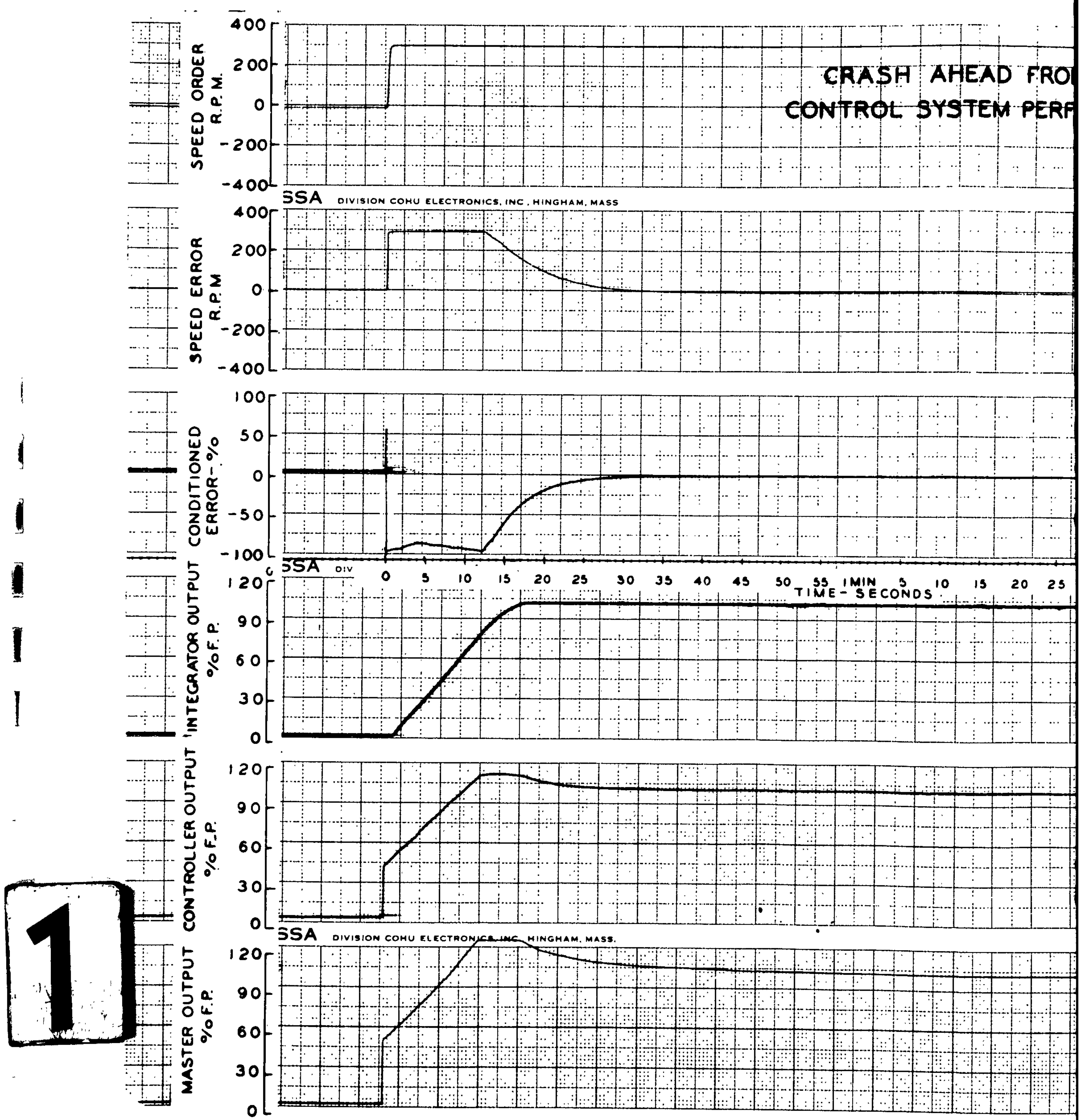

CRASH AHEAD FROM STOP
BOILER PERFORMANCE
NBTL PROJECT B-511
PRINTED IN U.S.A.
55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
SECONDS
2

FIG. 19B



CRASH AHEAD FRO
CONTROL SYSTEM PERF
SPEED ORDER R.P.M.
400
200
0
-200
-400
SSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
SPEED ERROR R.P.M
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
SSA
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25
TIME-SECONDS
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
SSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASTER OUTPUT %F.P.
120
90
60
30
0
1

CRASH AHEAD FROM STOP
CONTROL SYSTEM PERFORMANCE

NBTL PROJECT B-511

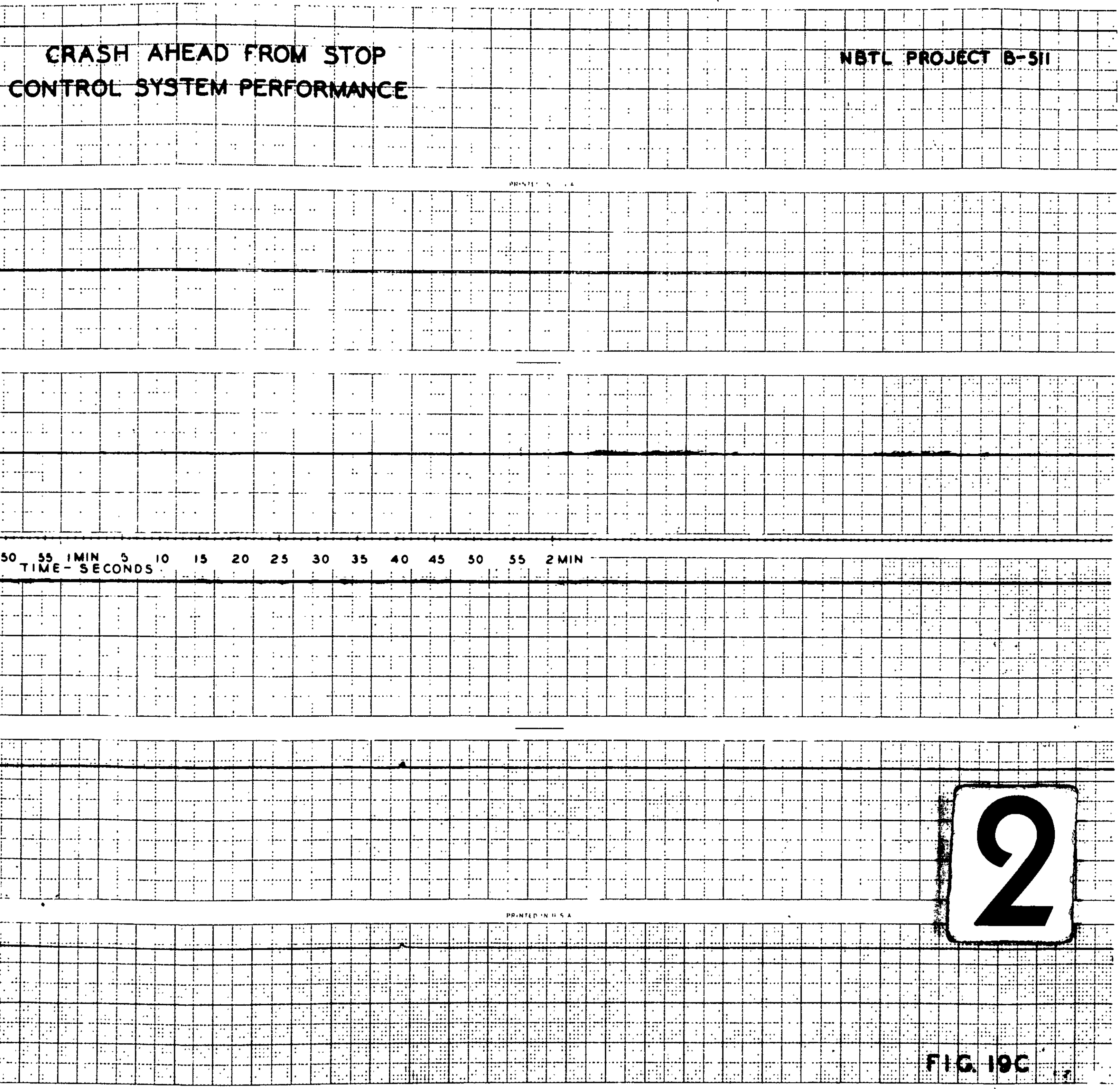
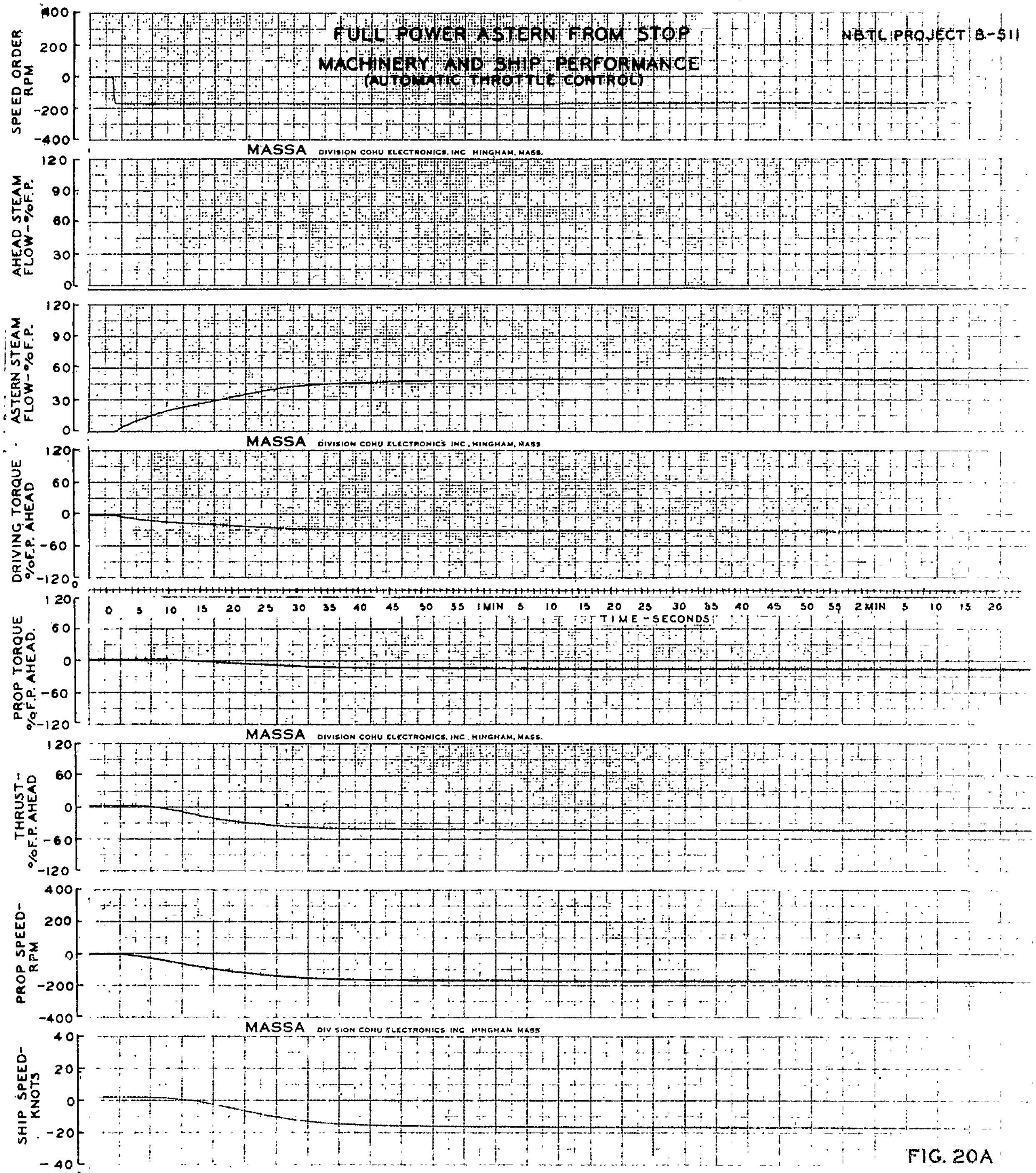
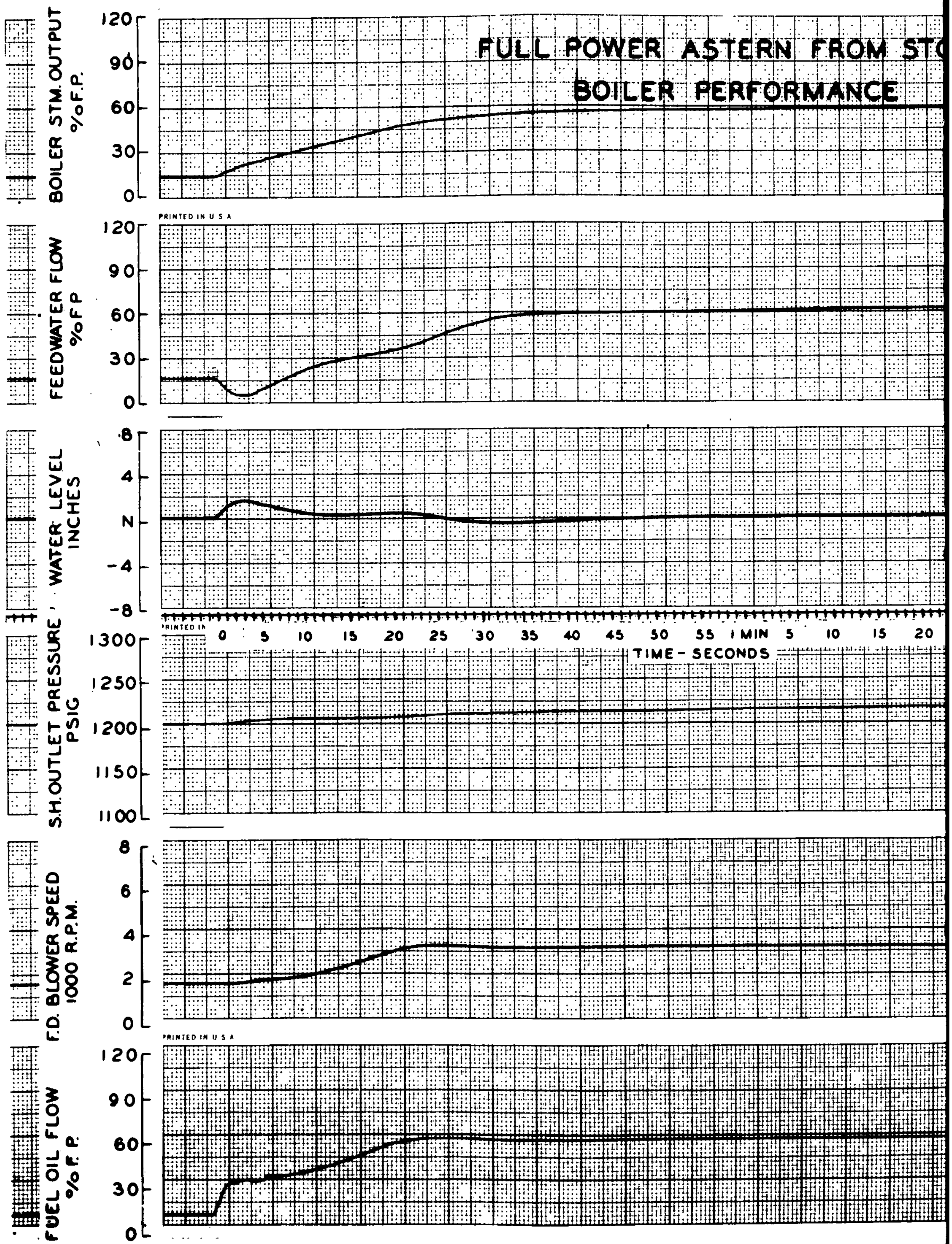


FIG. 19C


FULL POWER ASTERN FROM STOP
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
NBTL PROJECT B-511
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD.
THRUST-%F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
TIME-SECONDS
1 MIN
2 MIN
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.
FIG. 20A


FULL POWER ASTERN FROM STO
BOILER PERFORMANCE
BOILER STM. OUTPUT %F.P.
FEEDWATER FLOW %F.P.
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %F.P.
TIME - SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20
120 90 60 30 0
8 4 N -4 -8
1300 1250 1200 1150 1100
8 6 4 2 0
PRINTED IN U.S.A.

1

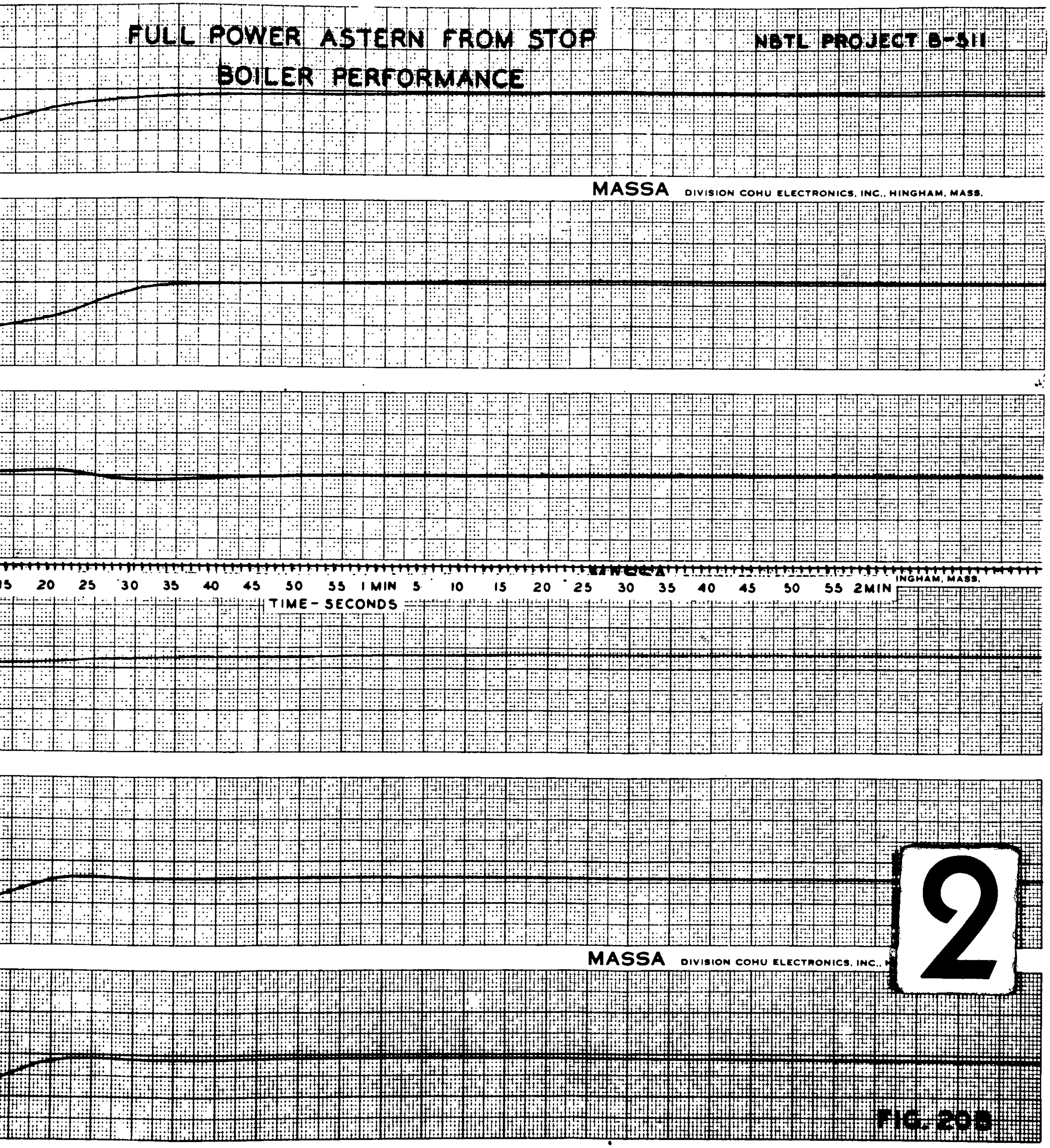
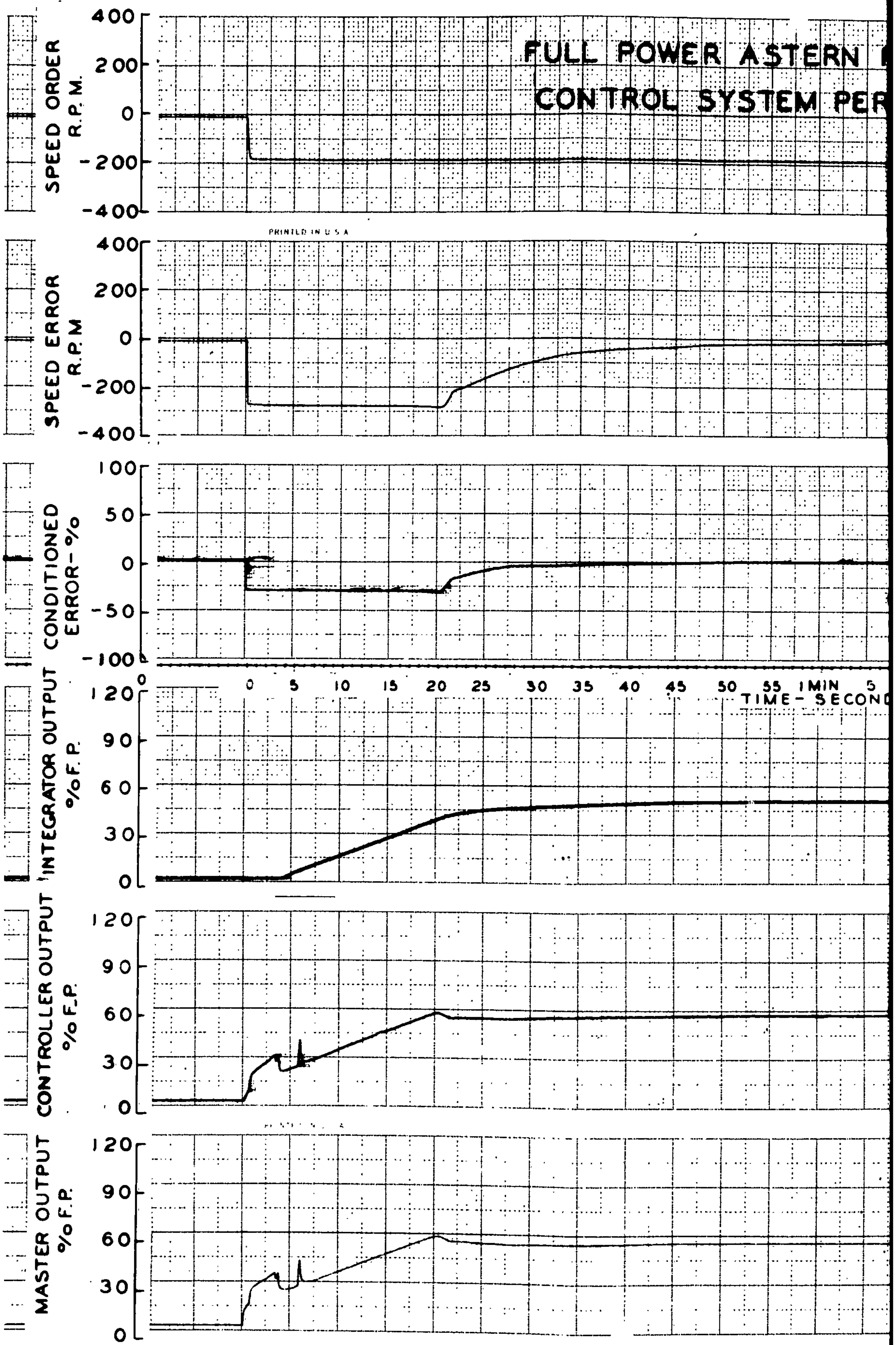

FULL POWER ASTERN FROM STOP
BOILER PERFORMANCE
NBTL PROJECT B-511
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC.
2

FIG. 20B

1


FULL POWER ASTERN
CONTROL SYSTEM PER
SPEED ORDER R.P.M.
400
200
0
-200
-400
PRINTED IN U.S.A.
SPEED ERROR R.P.M
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5
TIME-SECOND
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
MASTER OUTPUT %F.P.
120
90
60
30
0

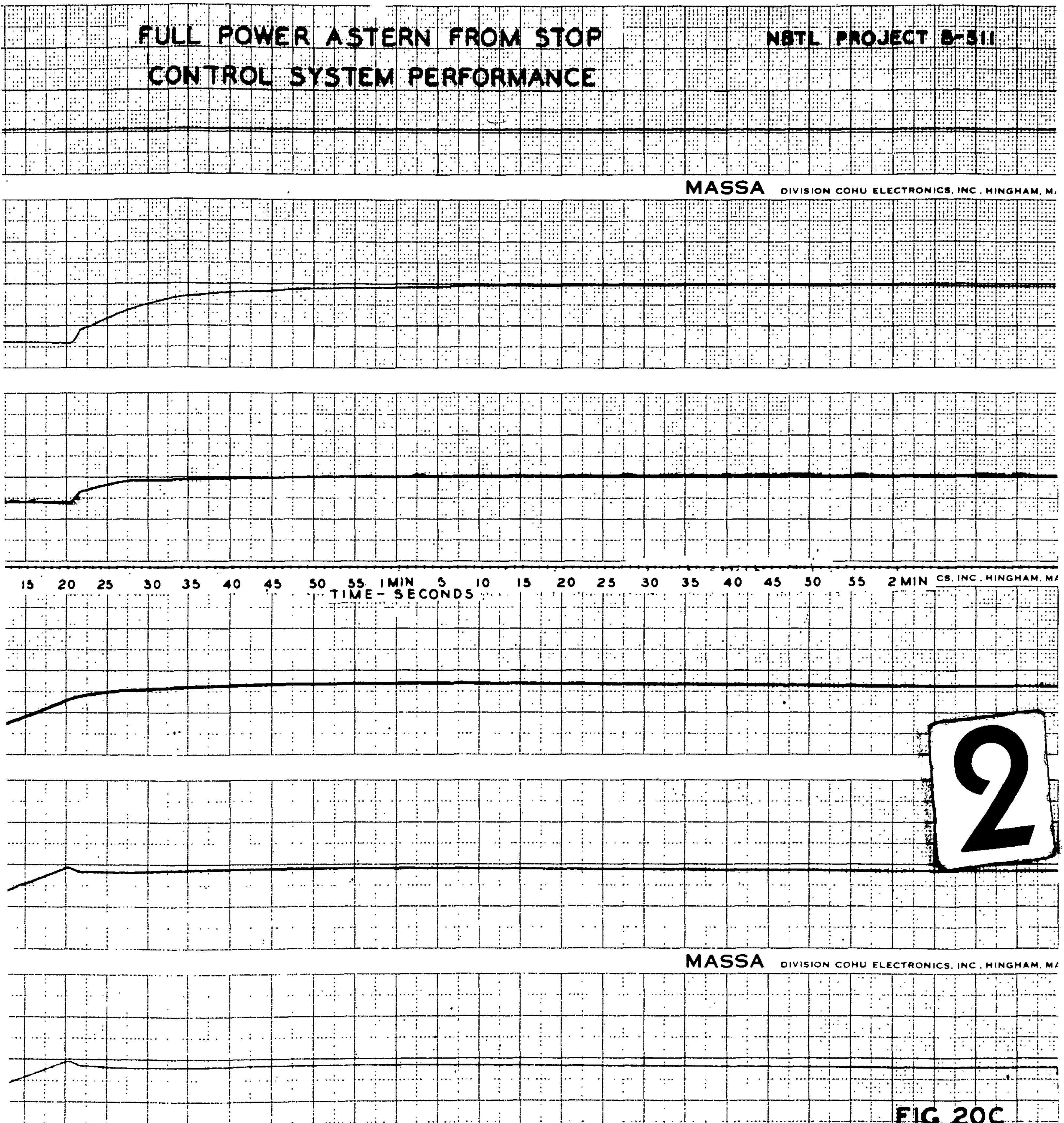
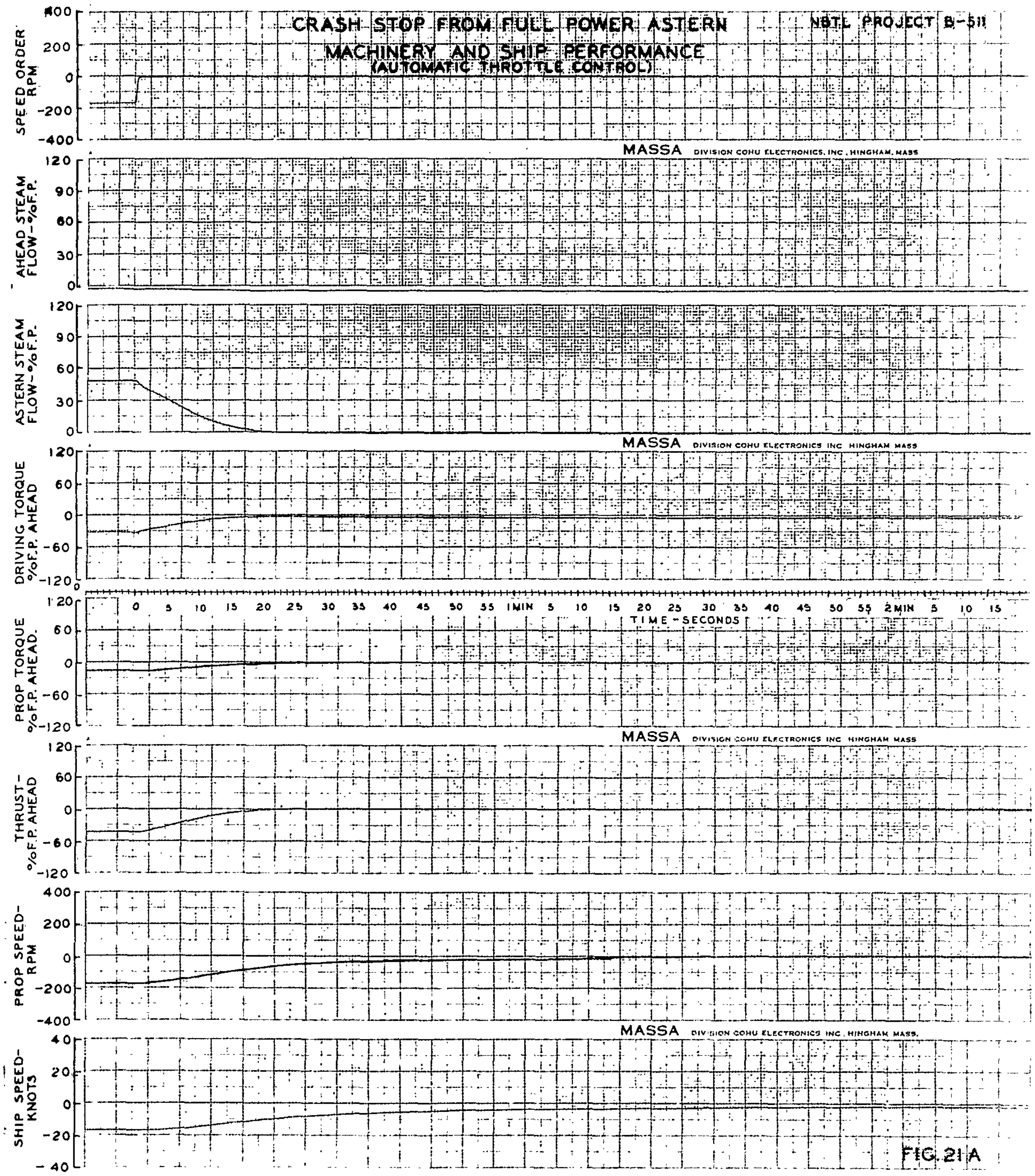
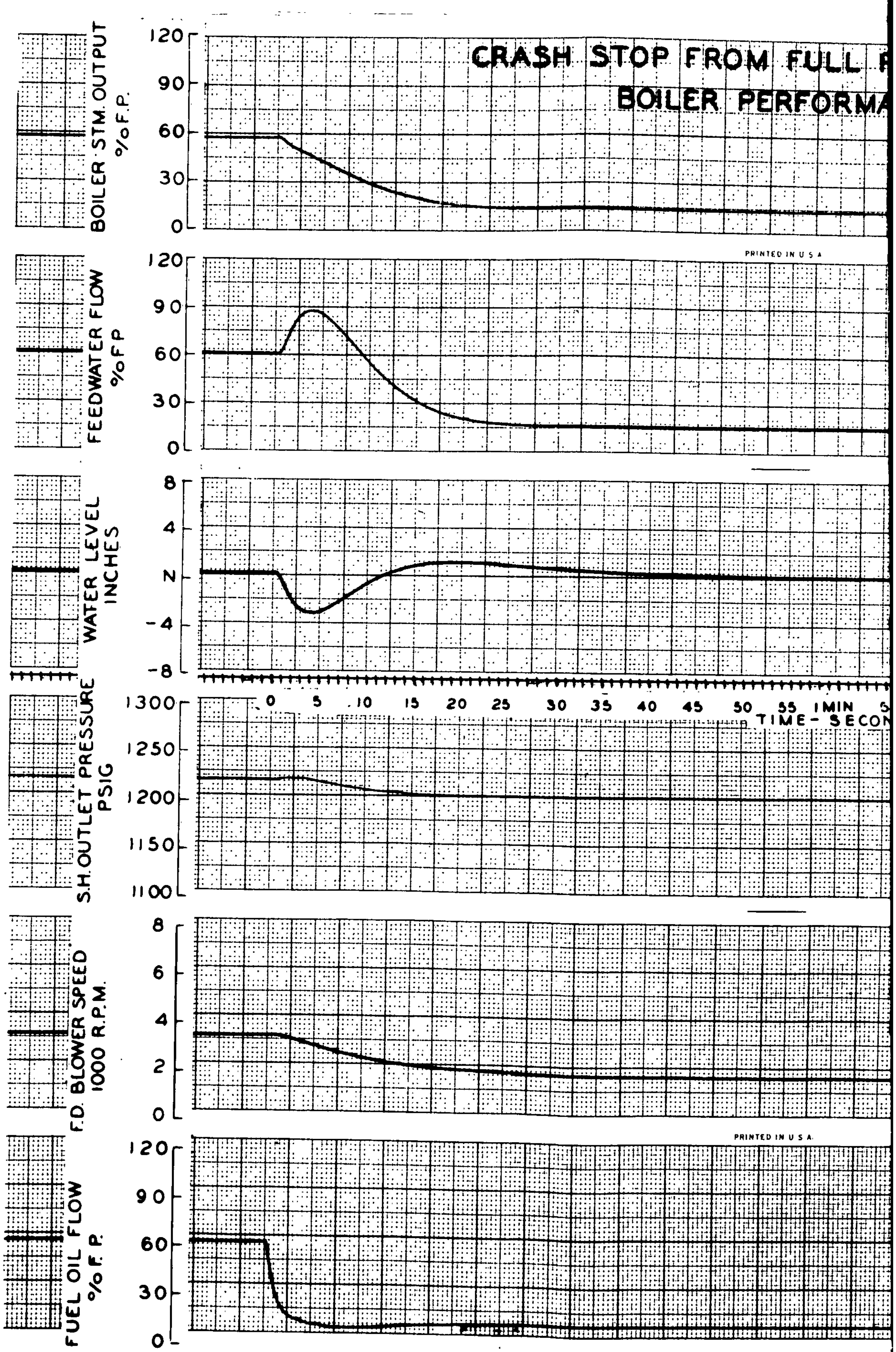

FULL POWER ASTERN FROM STOP
CONTROL SYSTEM PERFORMANCE
NBTL PROJECT B-511
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, M
15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, M

FIG. 20C



CRASH STOP FROM FULL POWER ASTERN
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
NBTL PROJECT B-511
SPEED ORDER RPM
400
200
0
-200
-400
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS
AHEAD STEAM FLOW-%F.P.
120
90
60
30
0
ASTERN STEAM FLOW-%F.P.
MASSA DIVISION COHU ELECTRONICS INC HINGHAM MASS
DRIVING TORQUE %F.P. AHEAD
60
-60
-120
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN 5 10 15
TIME - SECONDS
PROP TORQUE %F.P. AHEAD.
THRUST- %F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
40
20
-20
-40

FIG. 21 A



CRASH STOP FROM FULL
BOILER PERFORMA
BOILER STM. OUTPUT %o F.P.
120
90
60
30
0
FEEDWATER FLOW %o F P
WATER LEVEL INCHES
8
4
N
-4
-8
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN
TIME - SECON
S.H. OUTLET PRESSURE PSIG
1300
1250
1200
1150
1100
F.D. BLOWER SPEED 1000 R.P.M.
6
2
FUEL OIL FLOW %o F. P.
PRINTED IN U S A

1

CRASH STOP FROM FULL POWER ASTERN NBTL PROJECT B-511
BOILER PERFORMANCE

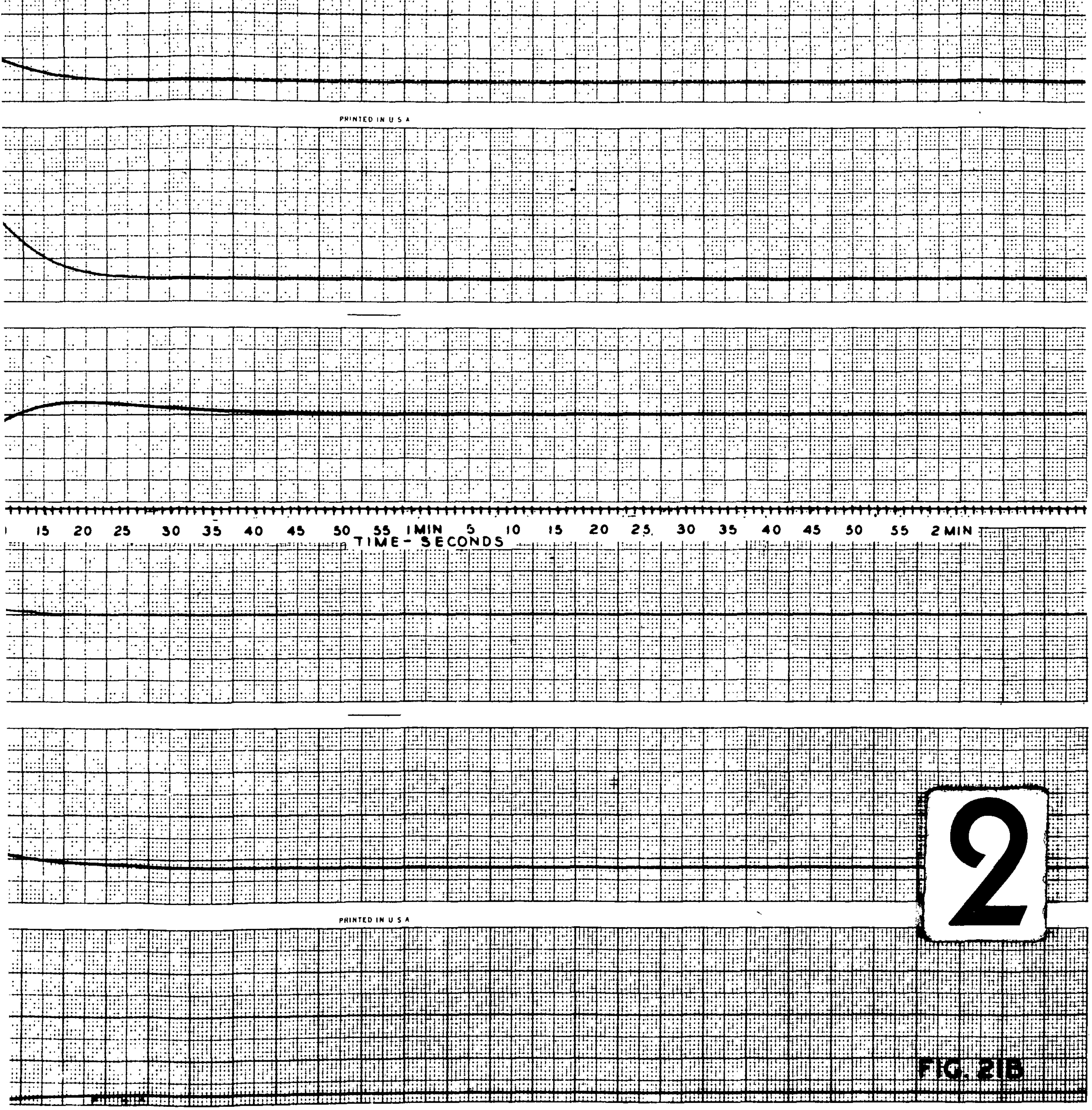
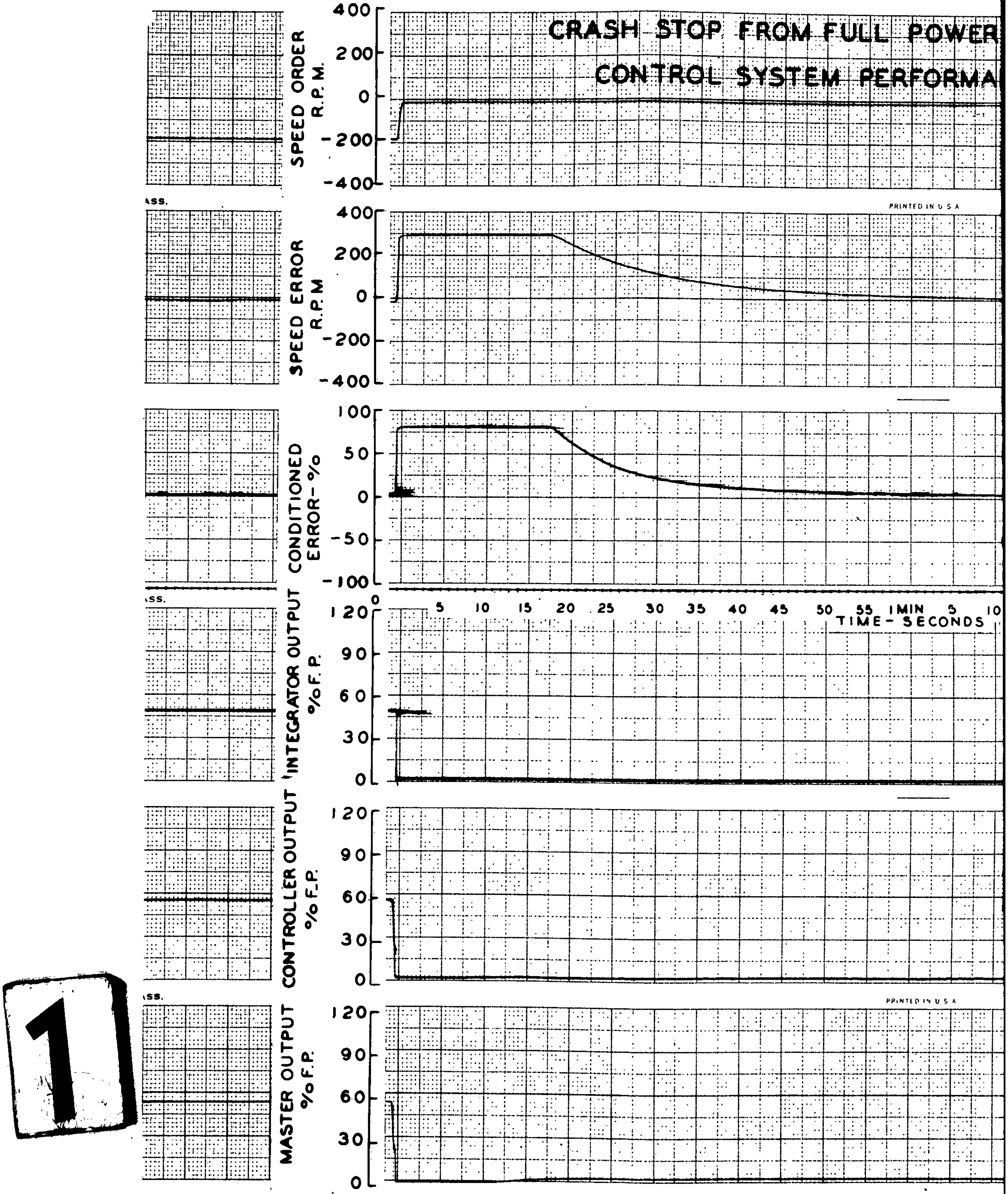


FIG. 21B


CRASH STOP FROM FULL POWER
CONTROL SYSTEM PERFORMA
SPEED ORDER R.P.M.
400
200
0
-200
-400
SPEED ERROR R.P.M
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
0
5
10
15
20
25
30
35
40
45
50
55
1MIN
5
10
TIME-SECONDS
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
MASTER OUTPUT %F.P.
120
90
60
30
0
PRINTED IN U.S.A.
1

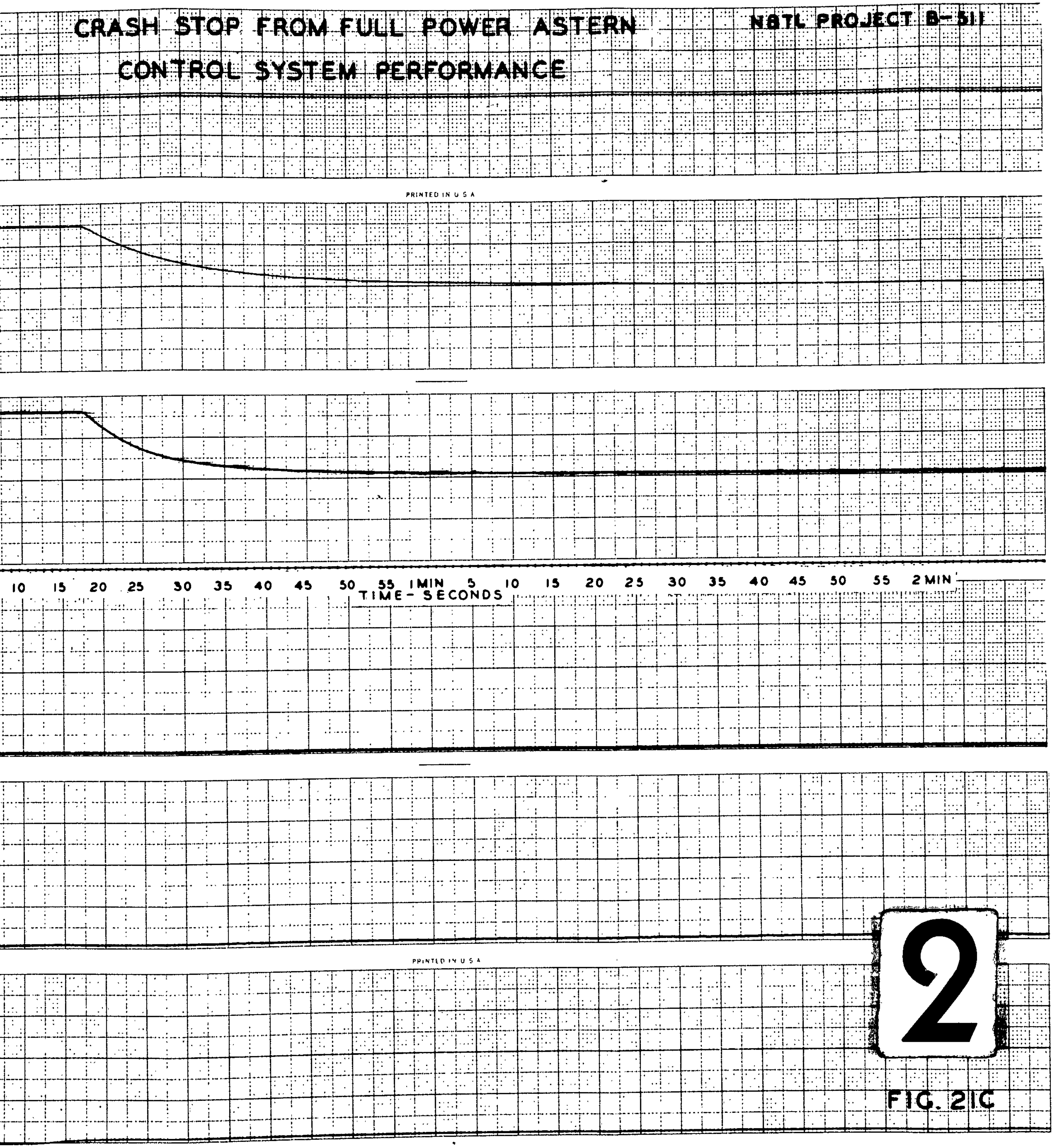
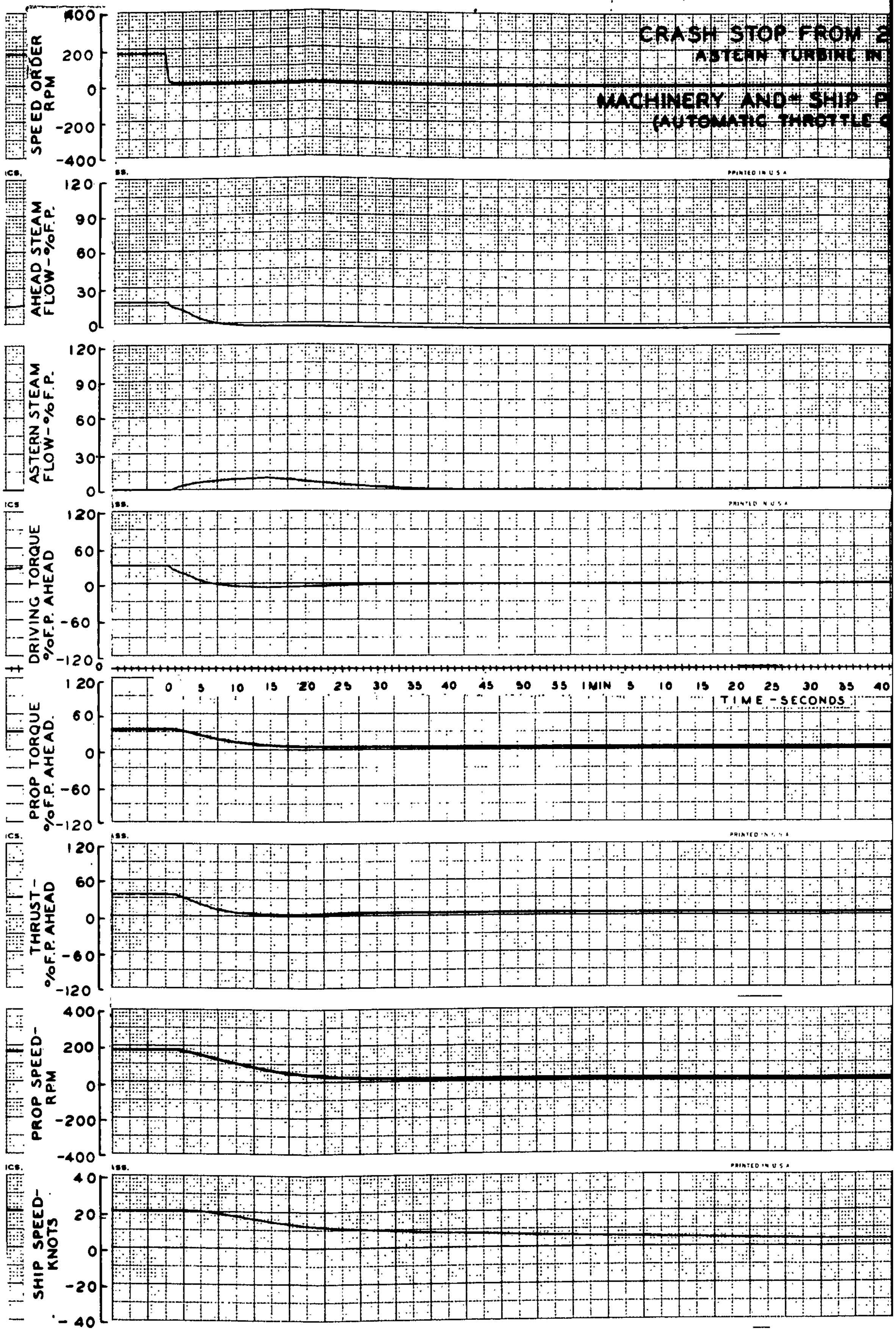

CRASH STOP FROM FULL POWER ASTERN
CONTROL SYSTEM PERFORMANCE
NBTL PROJECT B-511
PRINTED IN U S A
10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
PRINTED IN U S A
2

FIG. 21C


CRASH STOP FROM 2
ASTERN TURBINE IN
MACHINERY AND SHIP P
(AUTOMATIC THROTTLE C
SPEED ORDER RPM
AHEAD STEAM FLOW-%of F.P.
ASTERN STEAM FLOW-%of F.P.
DRIVING TORQUE %of F.P. AHEAD
PROP TORQUE %of F.P. AHEAD.
THRUST- %of F.P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
TIME - SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40
400 200 0 -200 -400
120 90 60 30 0
120 60 0 -60 -120
40 20 0 -20 -40
PRINTED IN U.S.A.

1

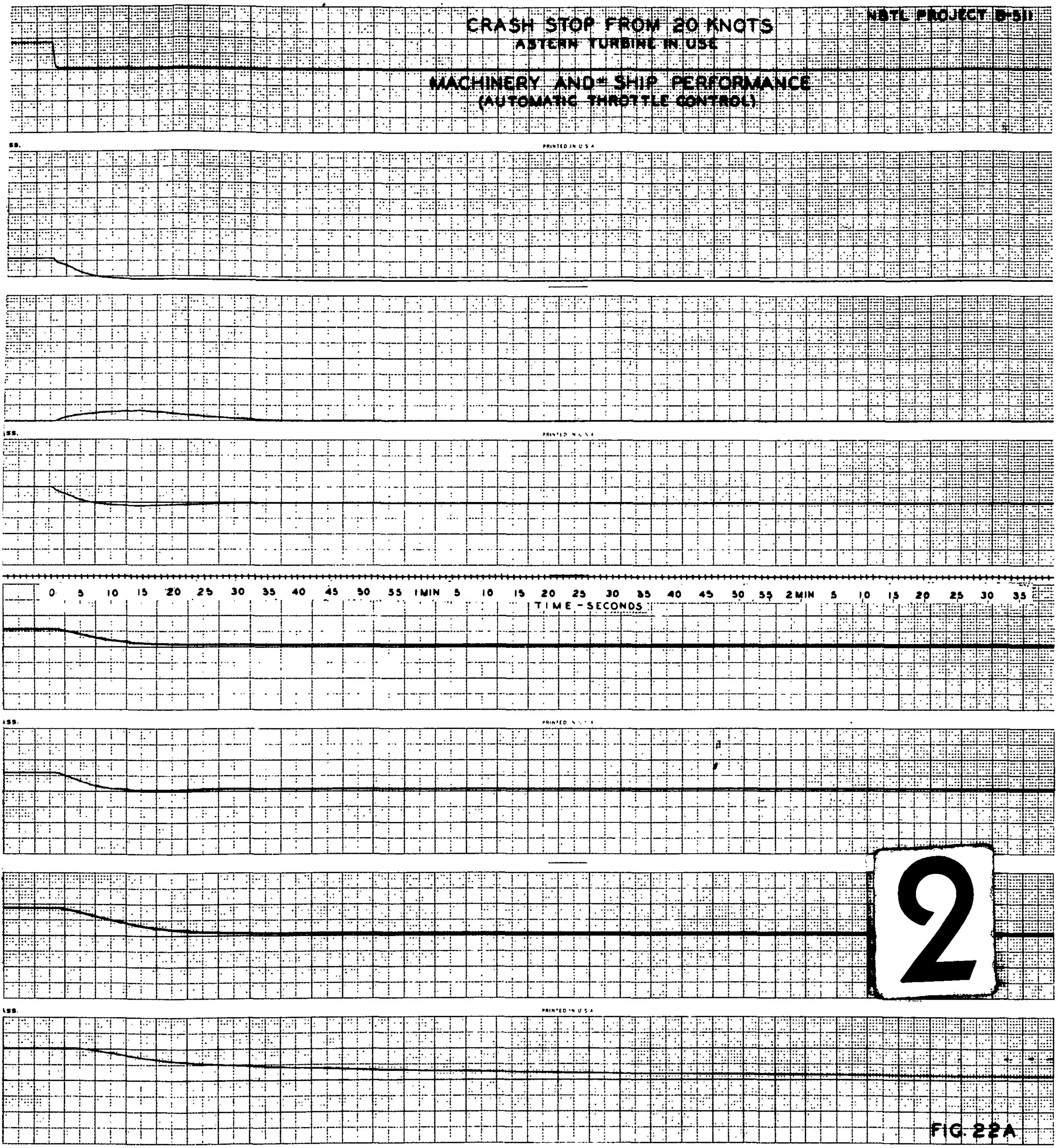
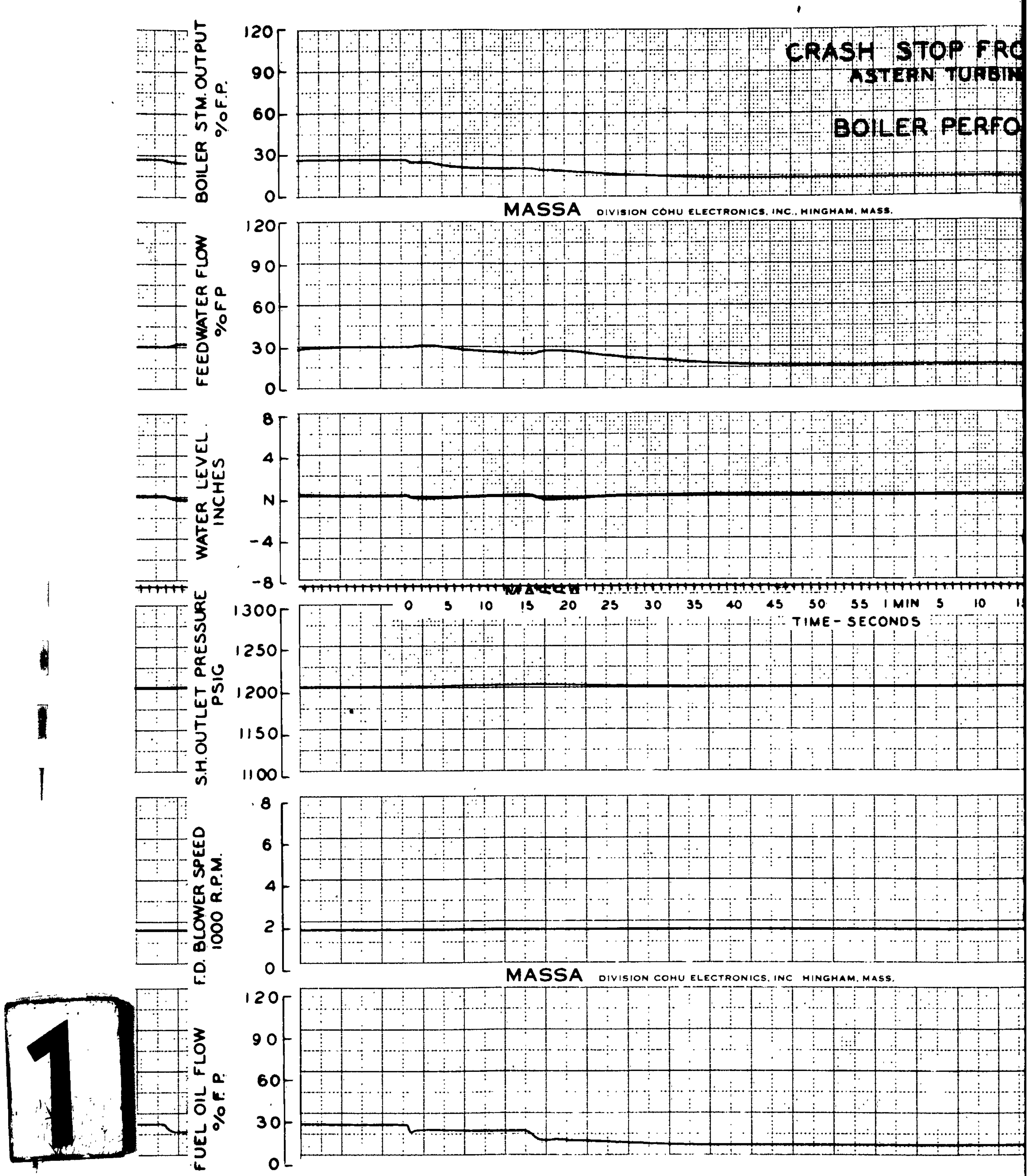
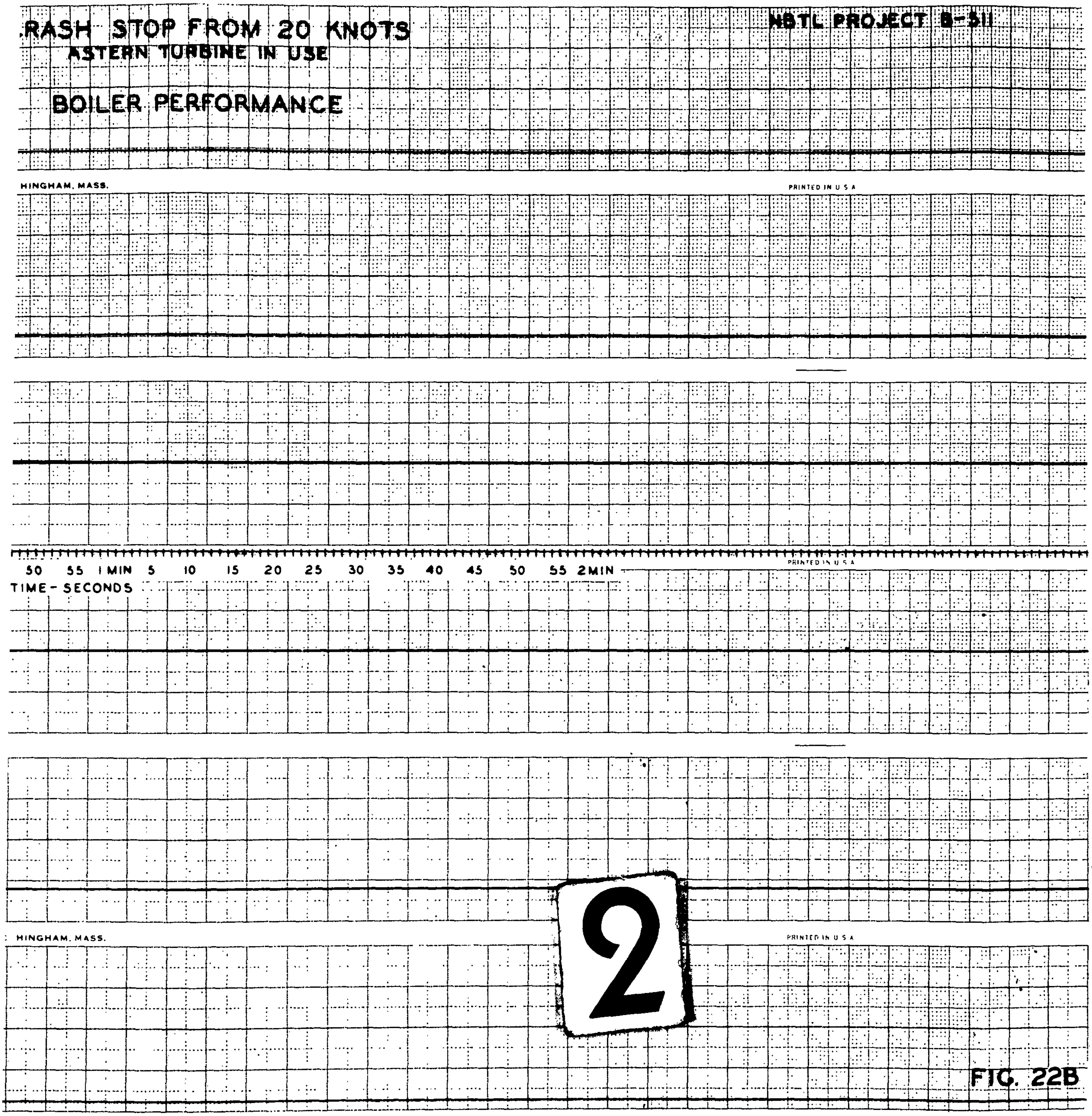

CRASH STOP FROM 20 KNOTS
ASTERN TURBINE IN USE
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
NBTL PROJECT B-511
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN 5 10 15 20 25 30 35
TIME - SECONDS

FIG. 22A

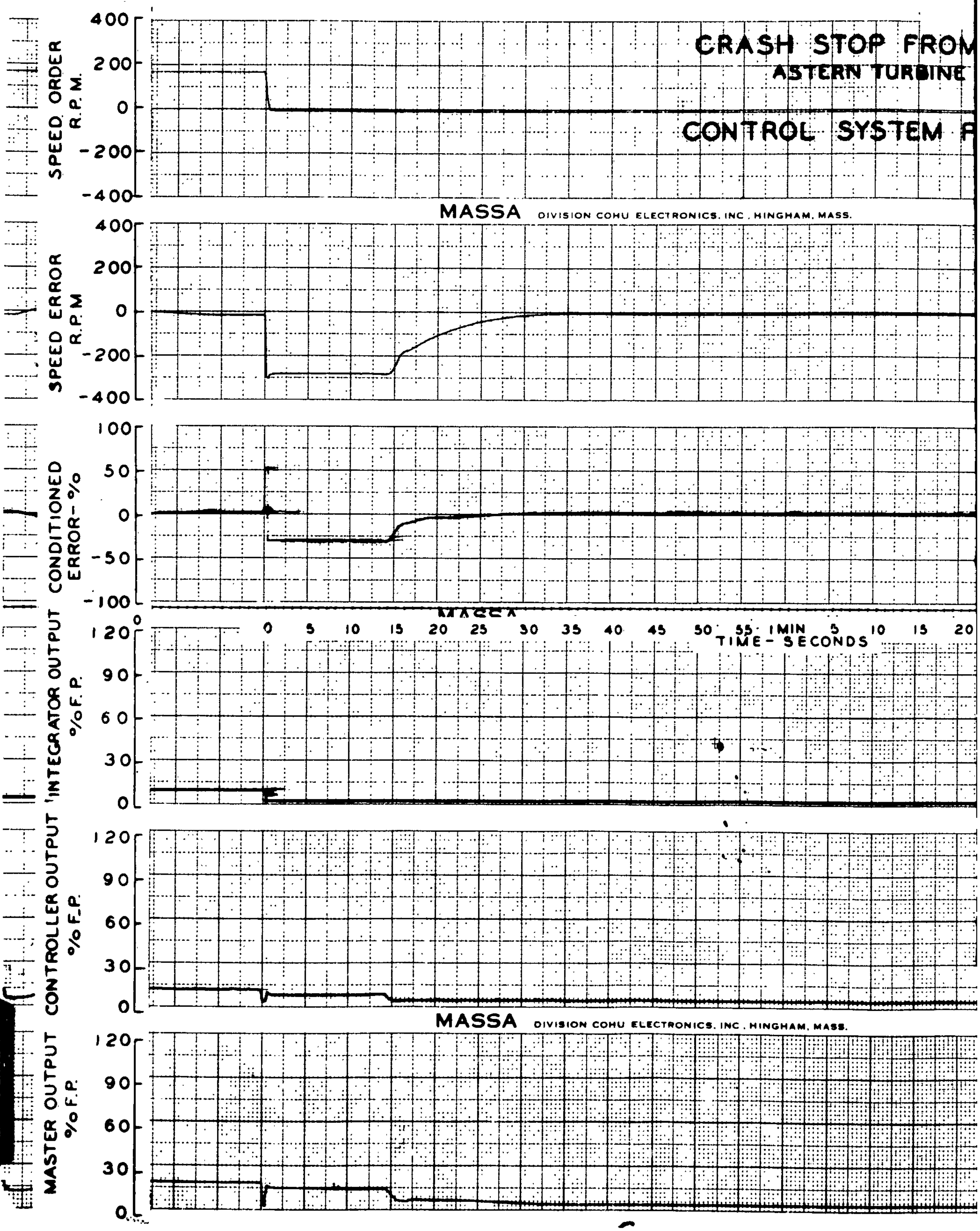


CRASH STOP FRO
ASTERN TURBIN
BOILER PERFO
BOILER STM. OUTPUT %F.P.
FEEDWATER FLOW %FP
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW % F.P.
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
1



CRASH STOP FROM 20 KNOTS
ASTERN TURBINE IN USE
BOILER PERFORMANCE
NBTL PROJECT B-511
HINGHAM, MASS.
PRINTED IN U S A
50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
PRINTED IN U S A
HINGHAM, MASS.
PRINTED IN U S A
2

FIG. 22B


CRASH STOP FROM
ASTERN TURBINE
CONTROL SYSTEM F
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
SPEED ORDER R.P.M.
400
200
0
-200
-400
SPEED ERROR R.P.M
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20
TIME-SECONDS
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASTER OUTPUT %F.P.
120
90
60
30
0

1

CRASH STOP FROM 20 KNOTS

ASTERN TURBINE IN USE

NBTL PROJECT B-511

CONTROL SYSTEM PERFORMANCE

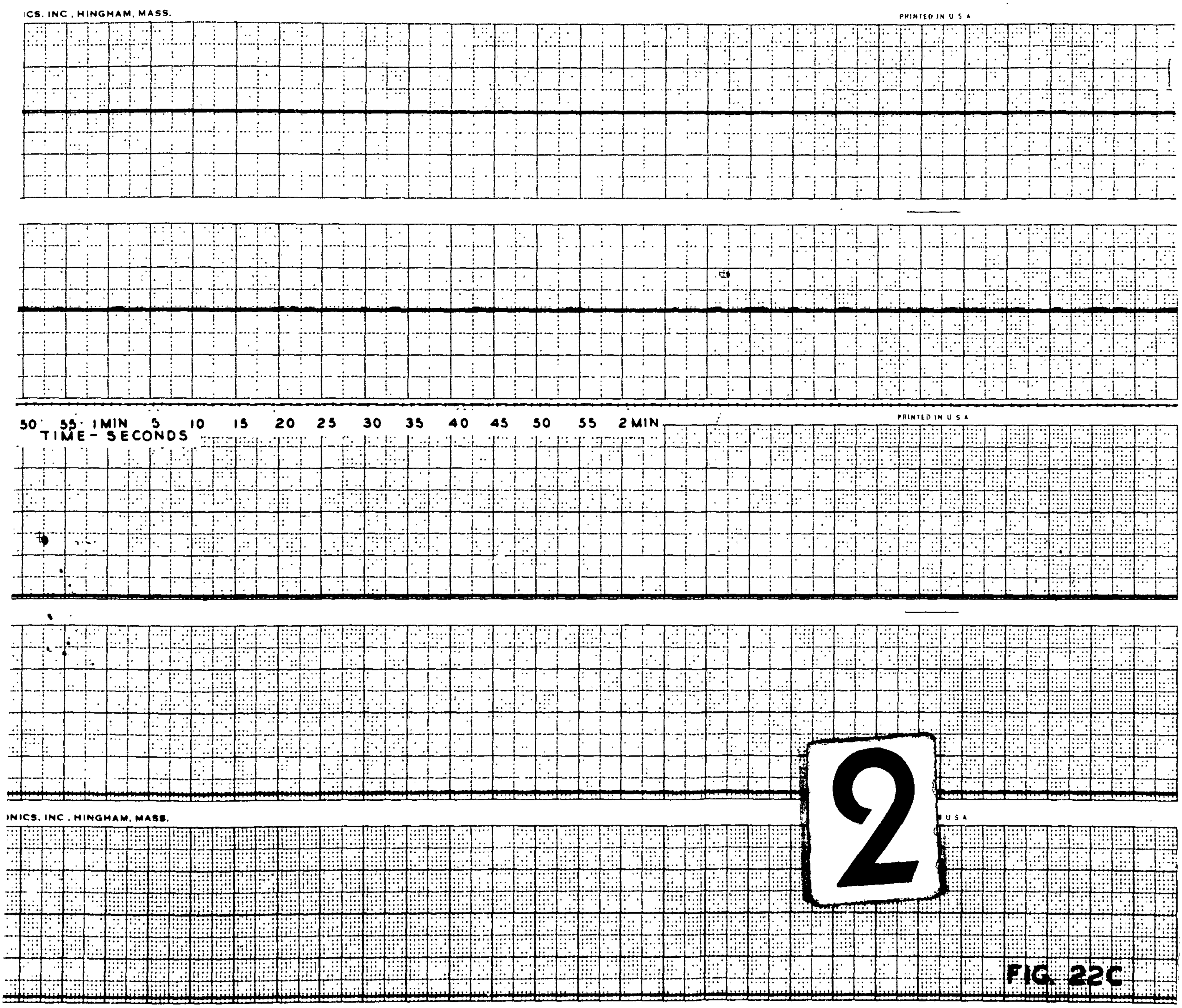
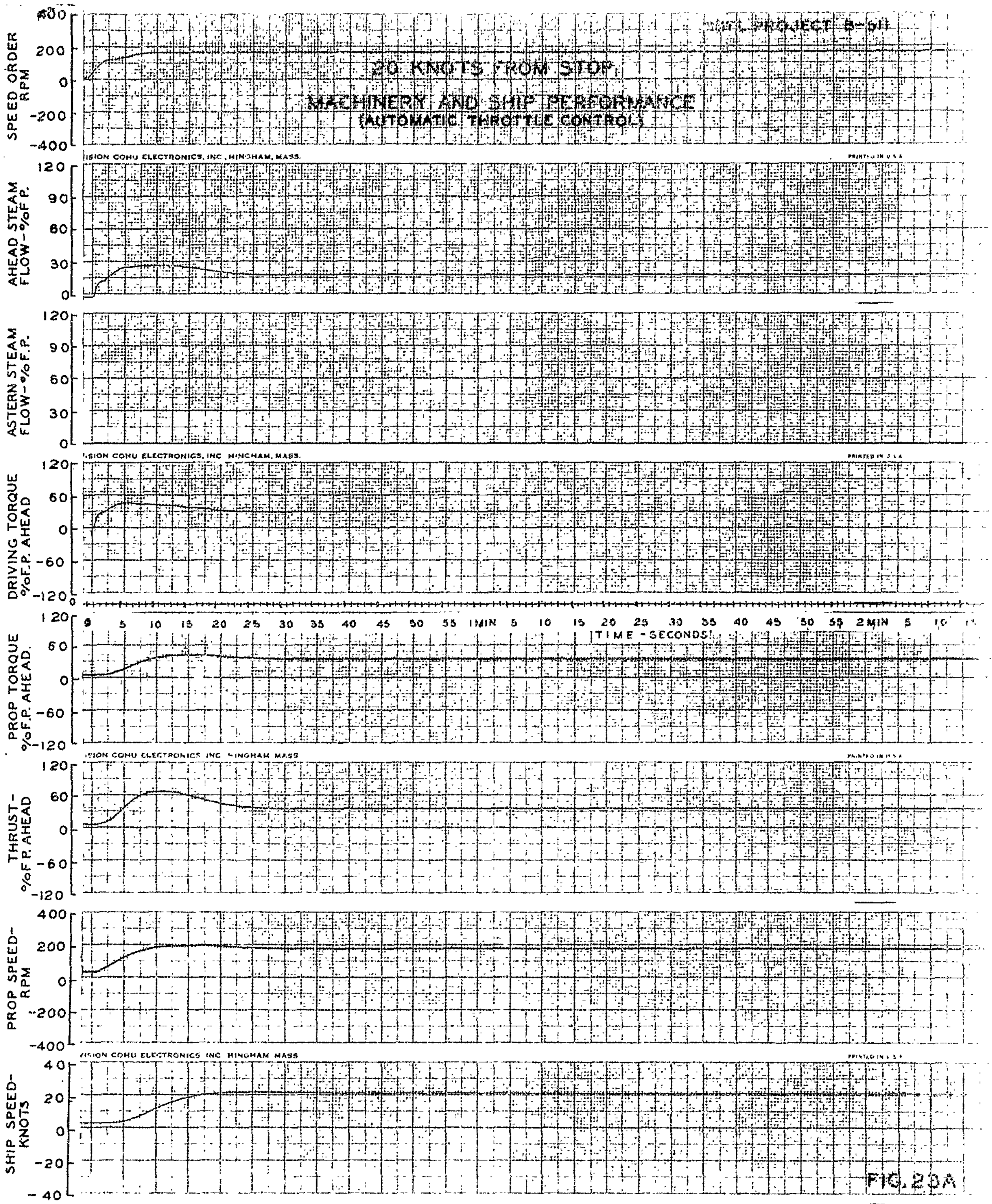
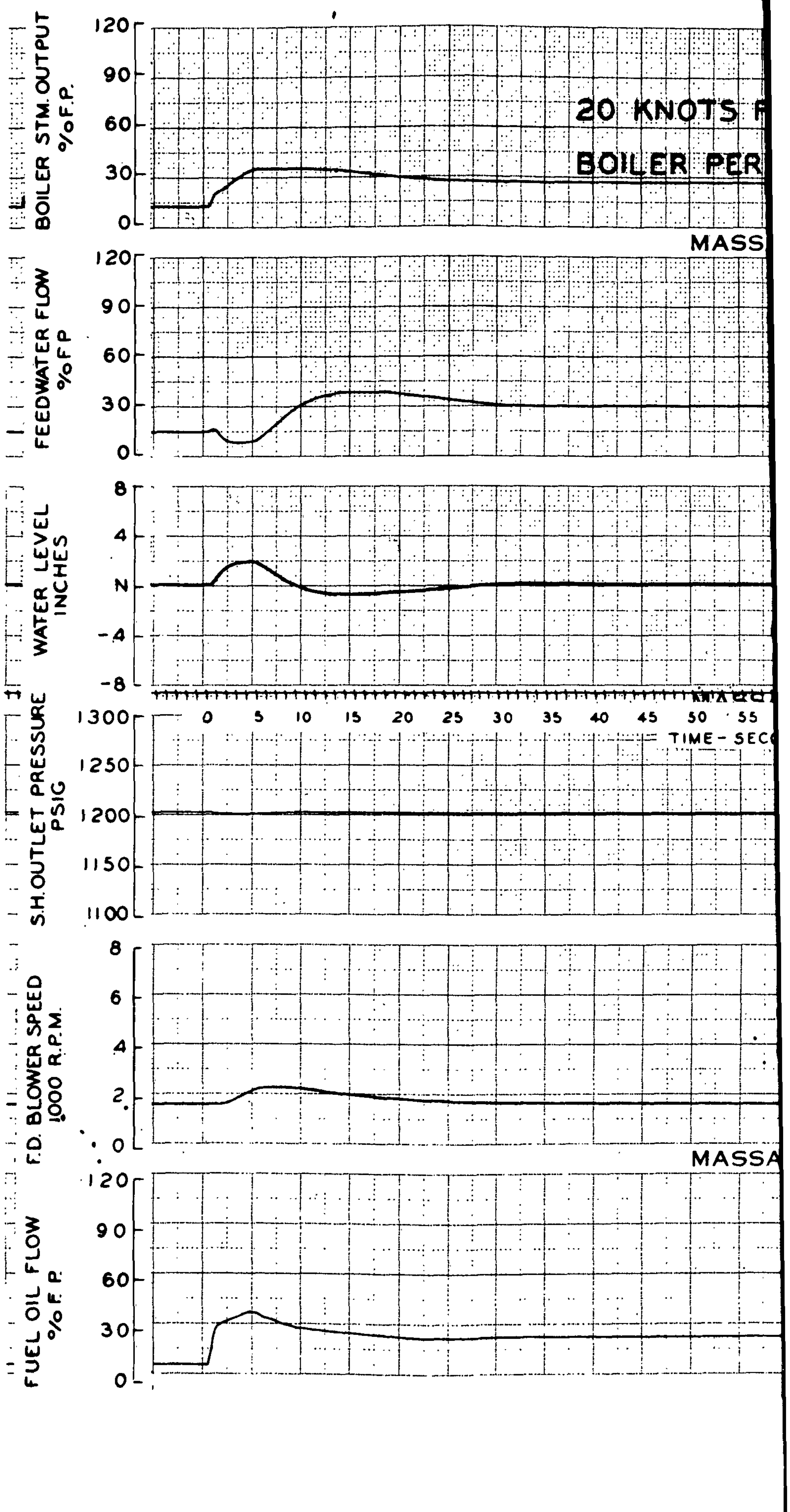


FIG. 22C


PROJECT B-511
20 KNOTS FROM STOP
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%OF P.
ASTERN STEAM FLOW-%OF.P.
DRIVING TORQUE %OF.P. AHEAD
PROP TORQUE %OF.P. AHEAD.
THRUST- %OF P. AHEAD
PROP SPEED- RPM
SHIP SPEED- KNOTS
TIME - SECONDS
1 MIN
2 MIN
COHU ELECTRONICS, INC. HINGHAM, MASS.
PRINTED IN U.S.A.
FIG. 23A


20 KNOTS F
BOILER PER
MASS
MASSA
BOILER STM. OUTPUT %F.P.
FEEDWATER FLOW %FP
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %F.P.
TIME - SEC
0
5
10
15
20
25
30
35
40
45
50
55
120
90
60
30
0
8
4
N
-4
-8
1300
1250
1200
1150
1100
6
2

1

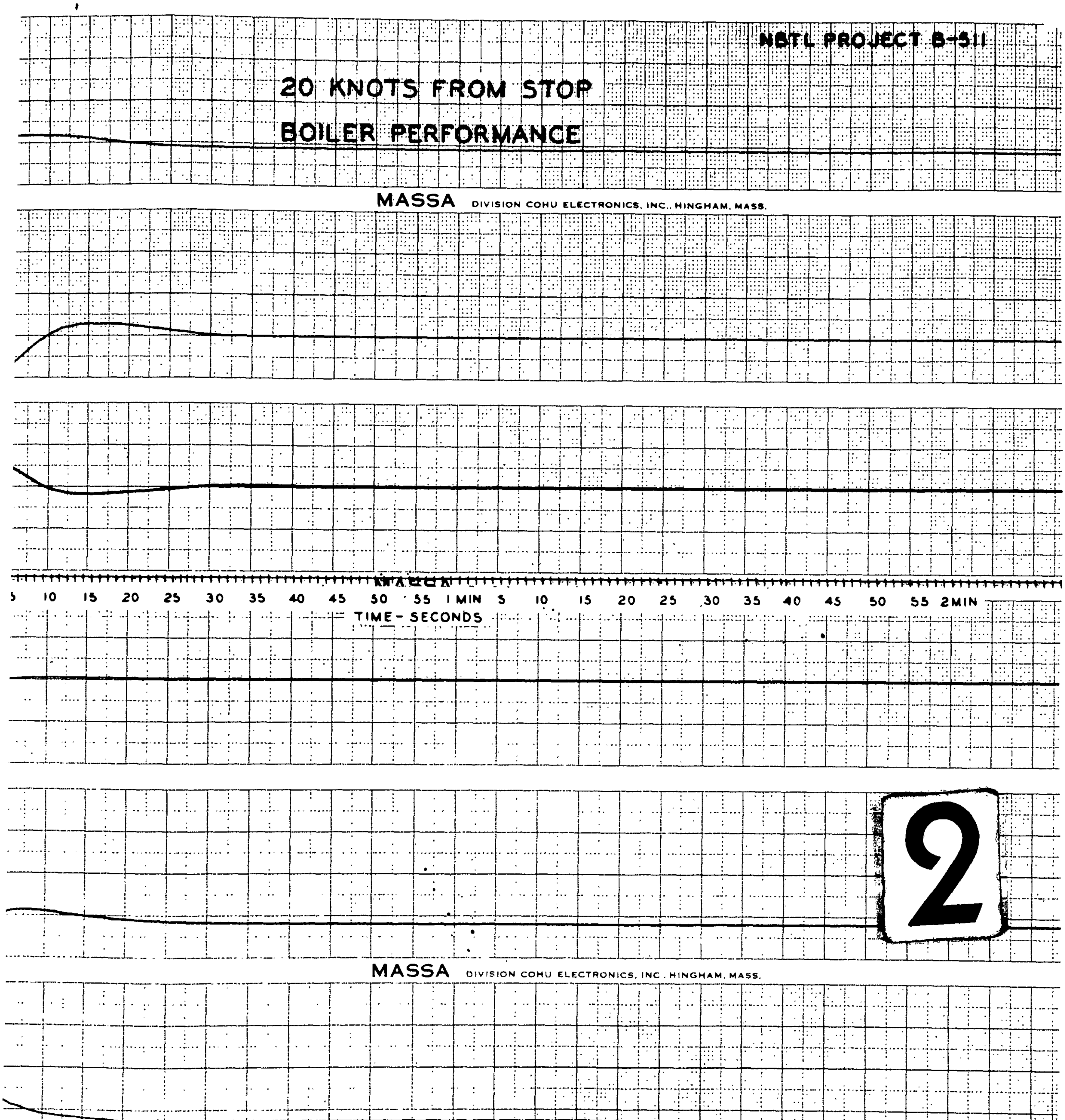
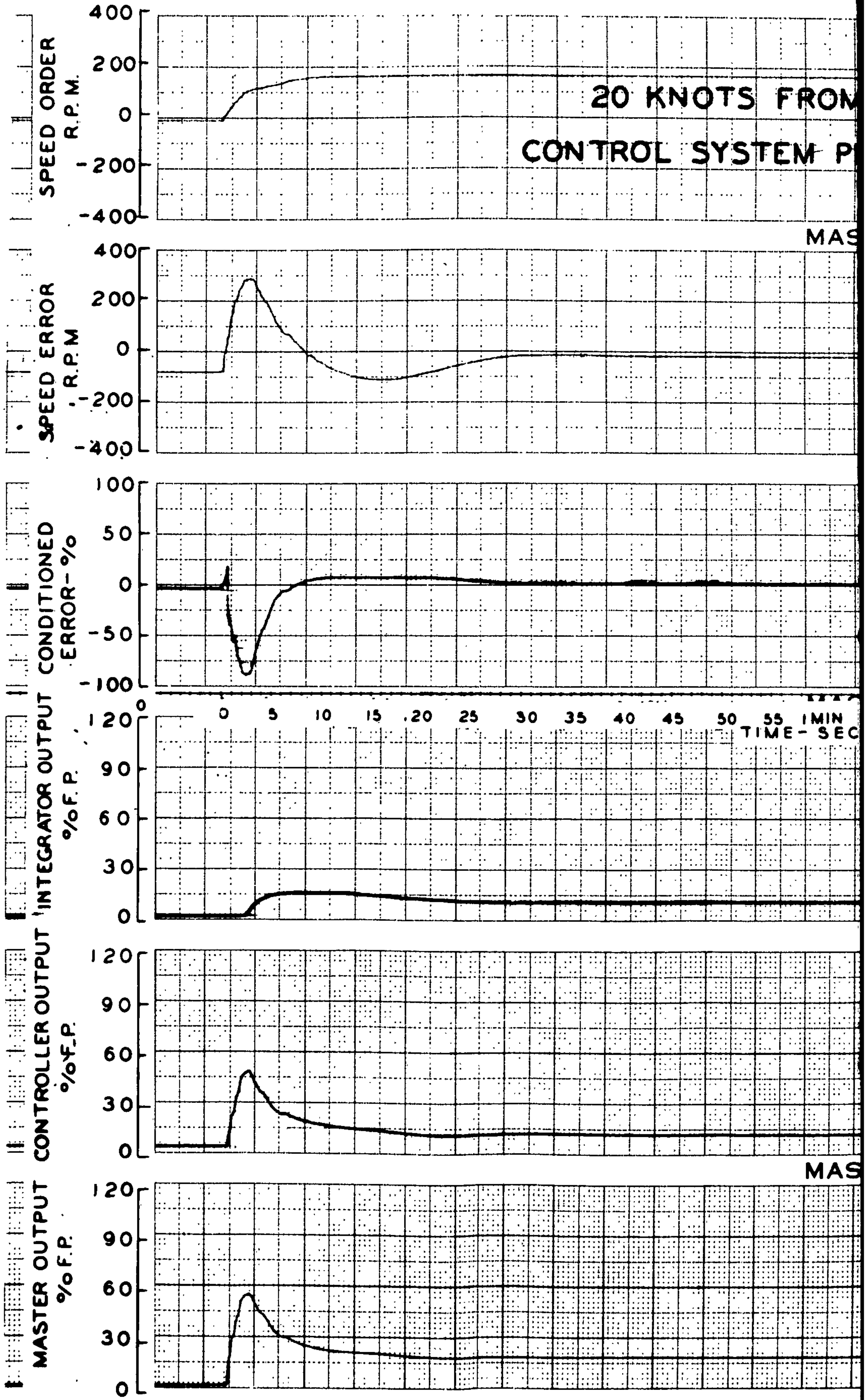

NBTL PROJECT B-511
20 KNOTS FROM STOP
BOILER PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
2
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.

FIG. 23 B


20 KNOTS FROM
CONTROL SYSTEM P
MAS
MAS
SPEED ORDER R.P.M.
SPEED ERROR R.P.M
CONDITIONED ERROR-%
INTEGRATOR OUTPUT %F.P.
CONTROLLER OUTPUT %F.P.
MASTER OUTPUT %F.P.
400
200
0
-200
-400
100
50
-50
-100
120
90
60
30
0 5 10 15 20 25 30 35 40 45 50 55 1MIN
TIME-SEC

1

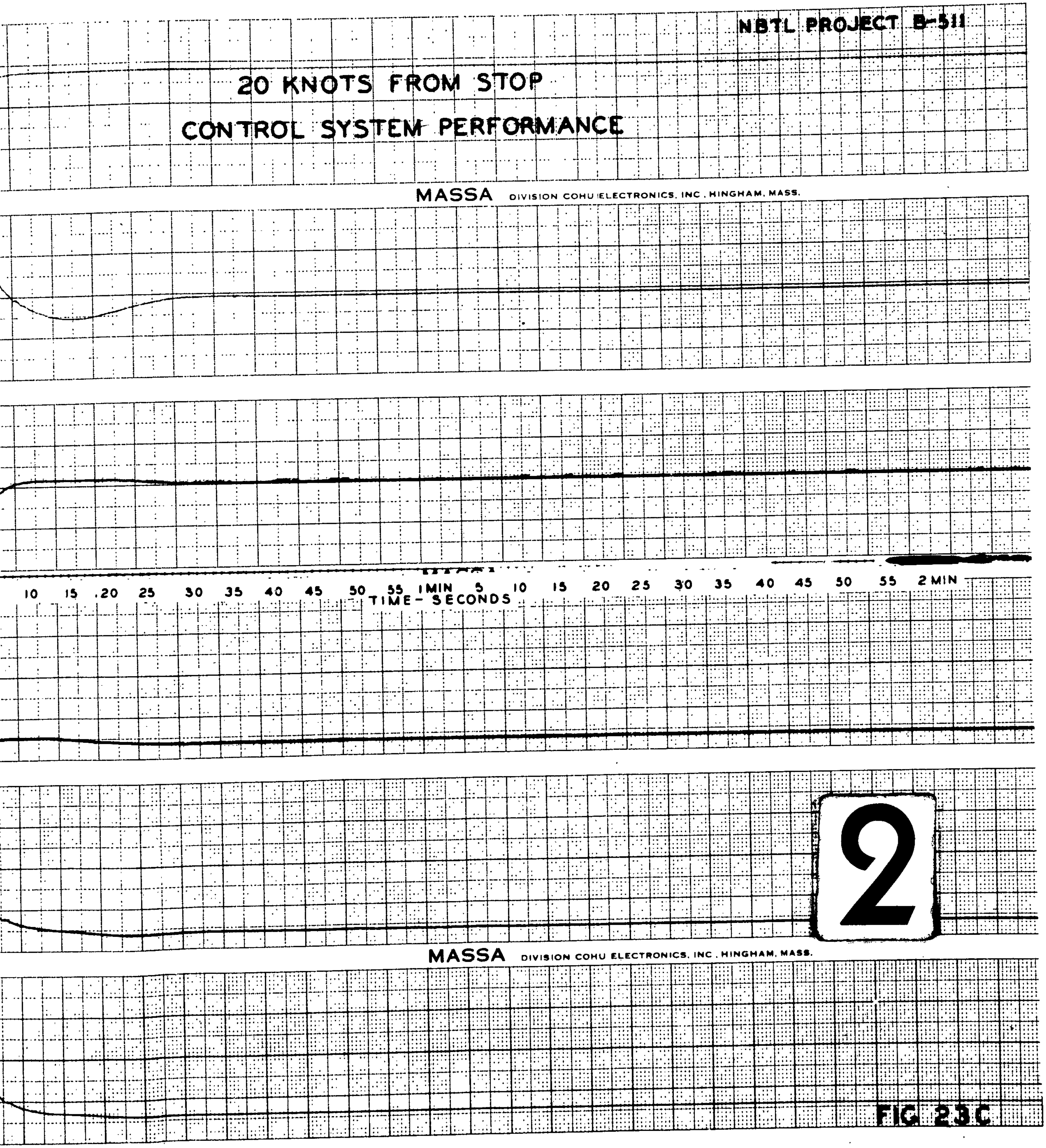

NBTL PROJECT B-511
20 KNOTS FROM STOP
CONTROL SYSTEM PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.
10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
2
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.

FIG 23C

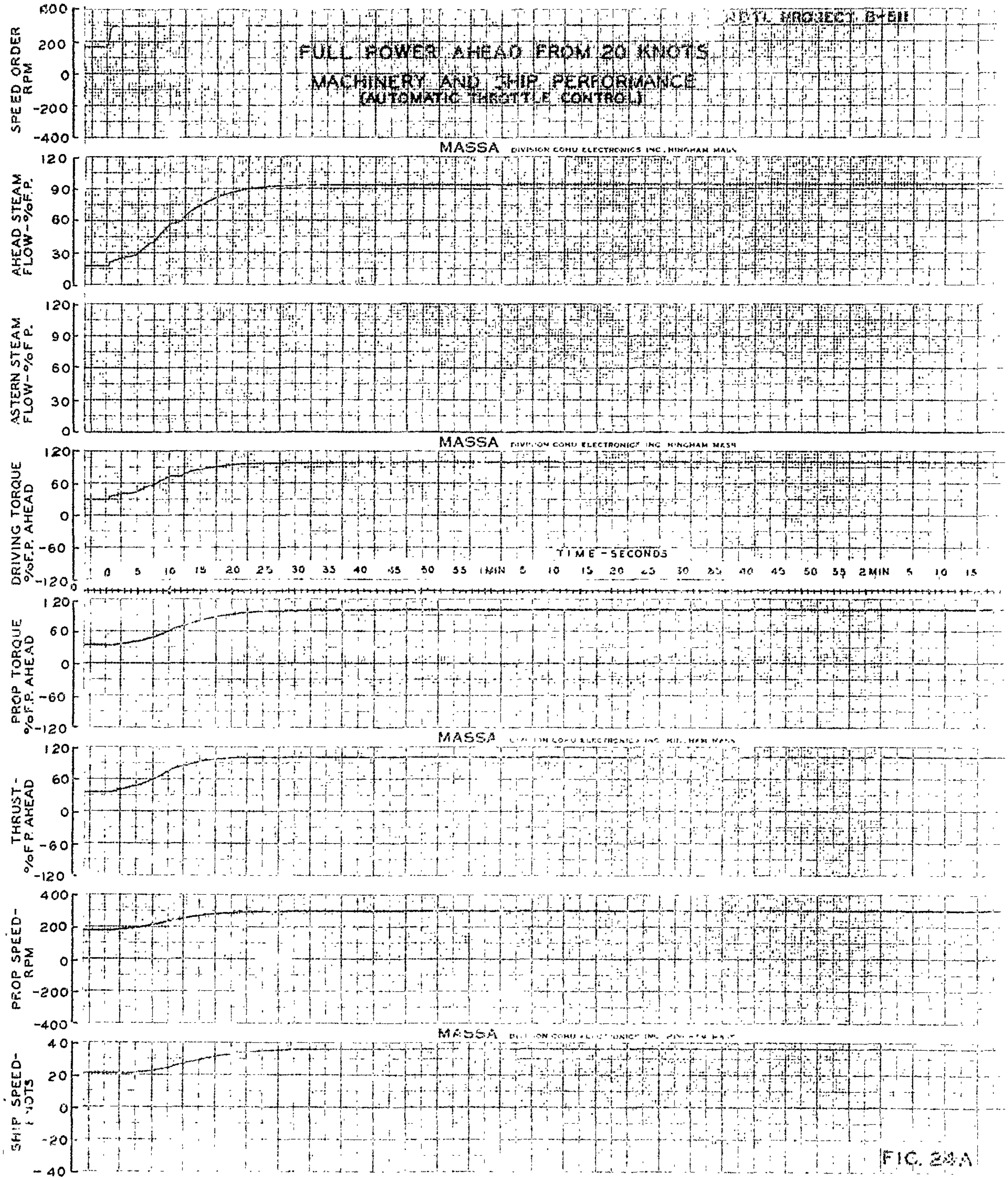
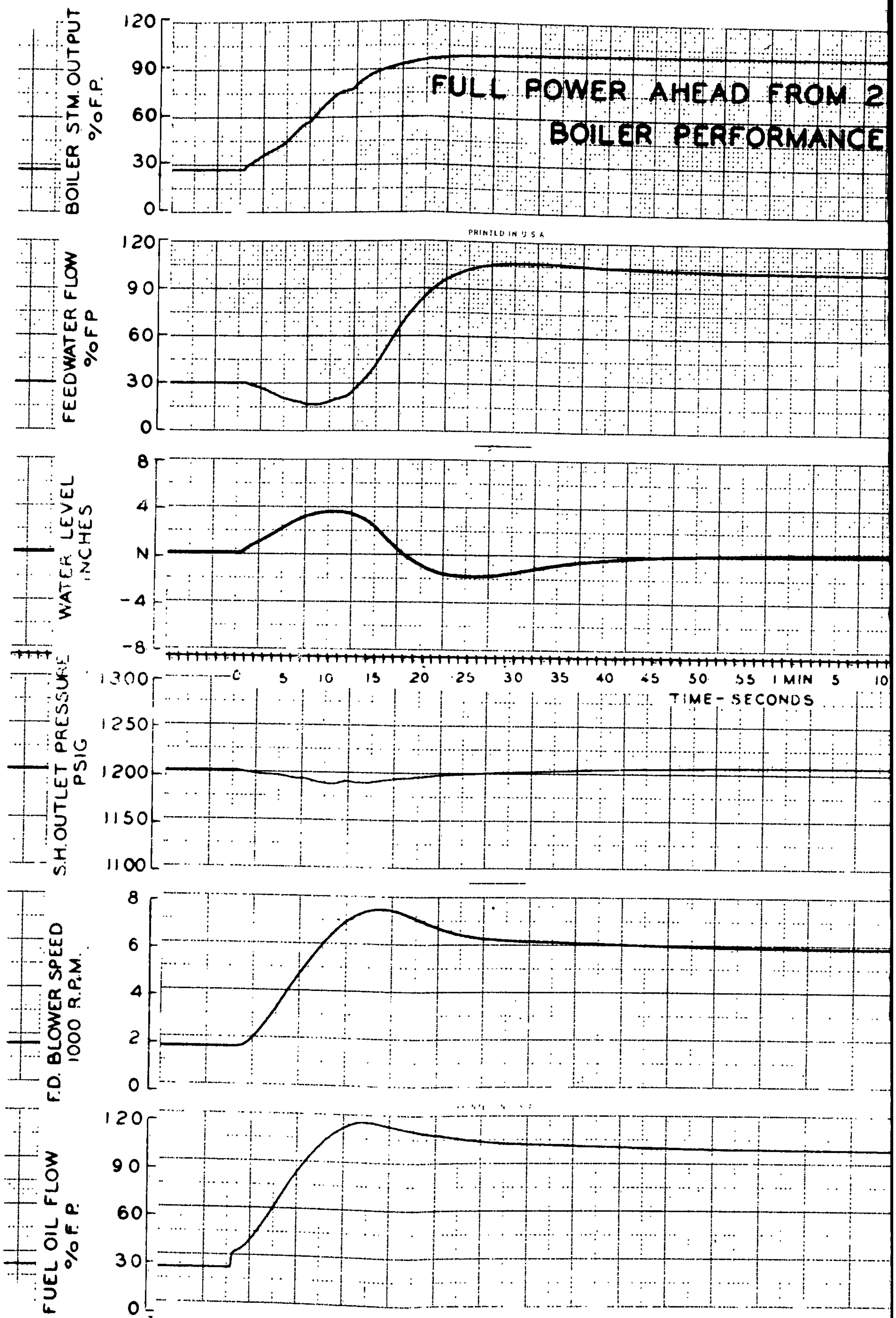

FULL POWER AHEAD FROM 20 KNOTS
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
MASSA
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
PROP TORQUE %F.P. AHEAD
THRUST-%F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
TIME-SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN 5 10 15

FIG. 24A



FULL POWER AHEAD FROM 2
BOILER PERFORMANCE
BOILER STM. OUTPUT %F.P.
FEEDWATER FLOW %F.P.
WATER LEVEL INCHES
S.H. OUTLET PRESSURE PSIG
F.D. BLOWER SPEED 1000 R.P.M.
FUEL OIL FLOW %F.P.
TIME - SECONDS
PRINTED IN U.S.A.

1

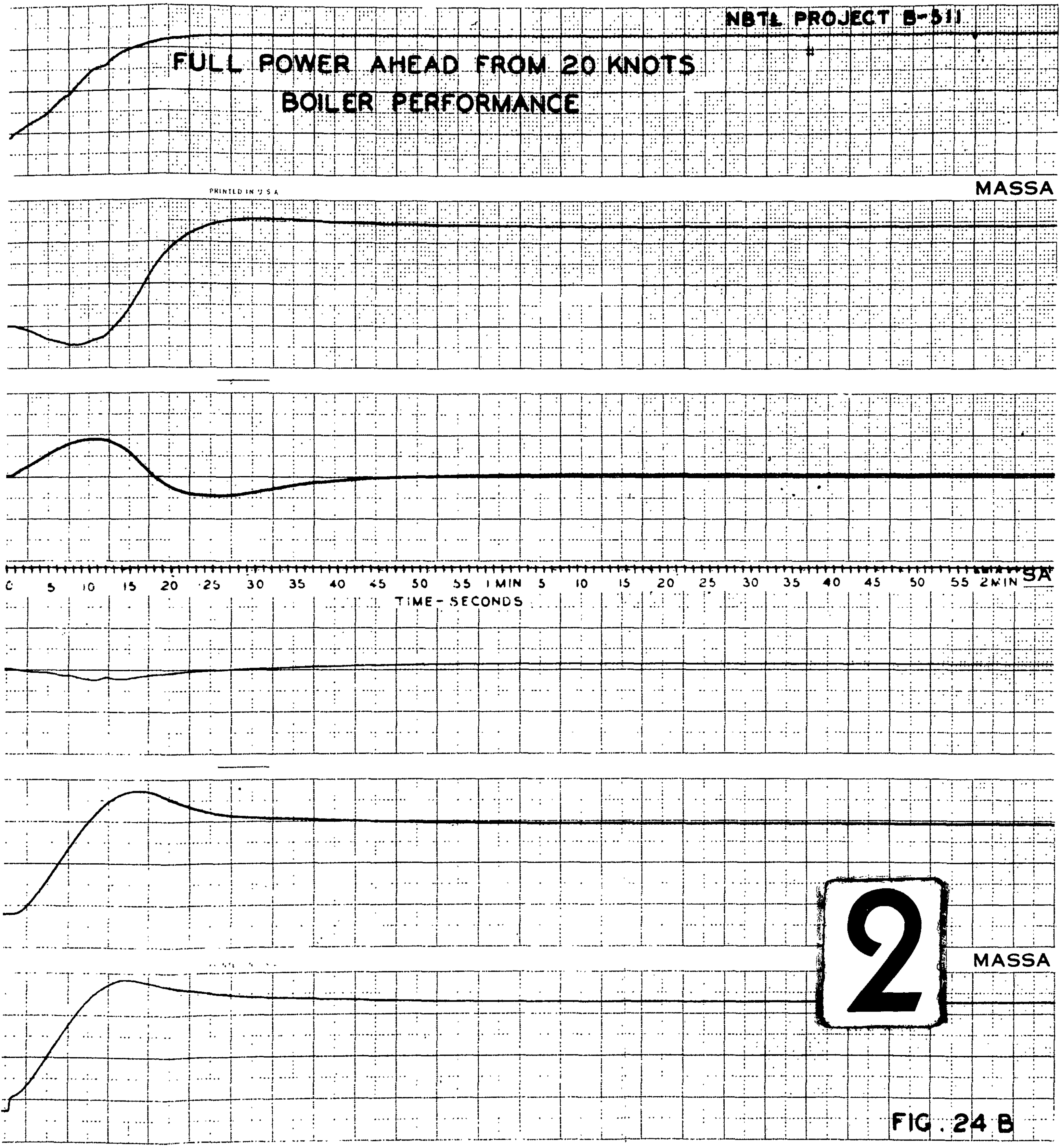
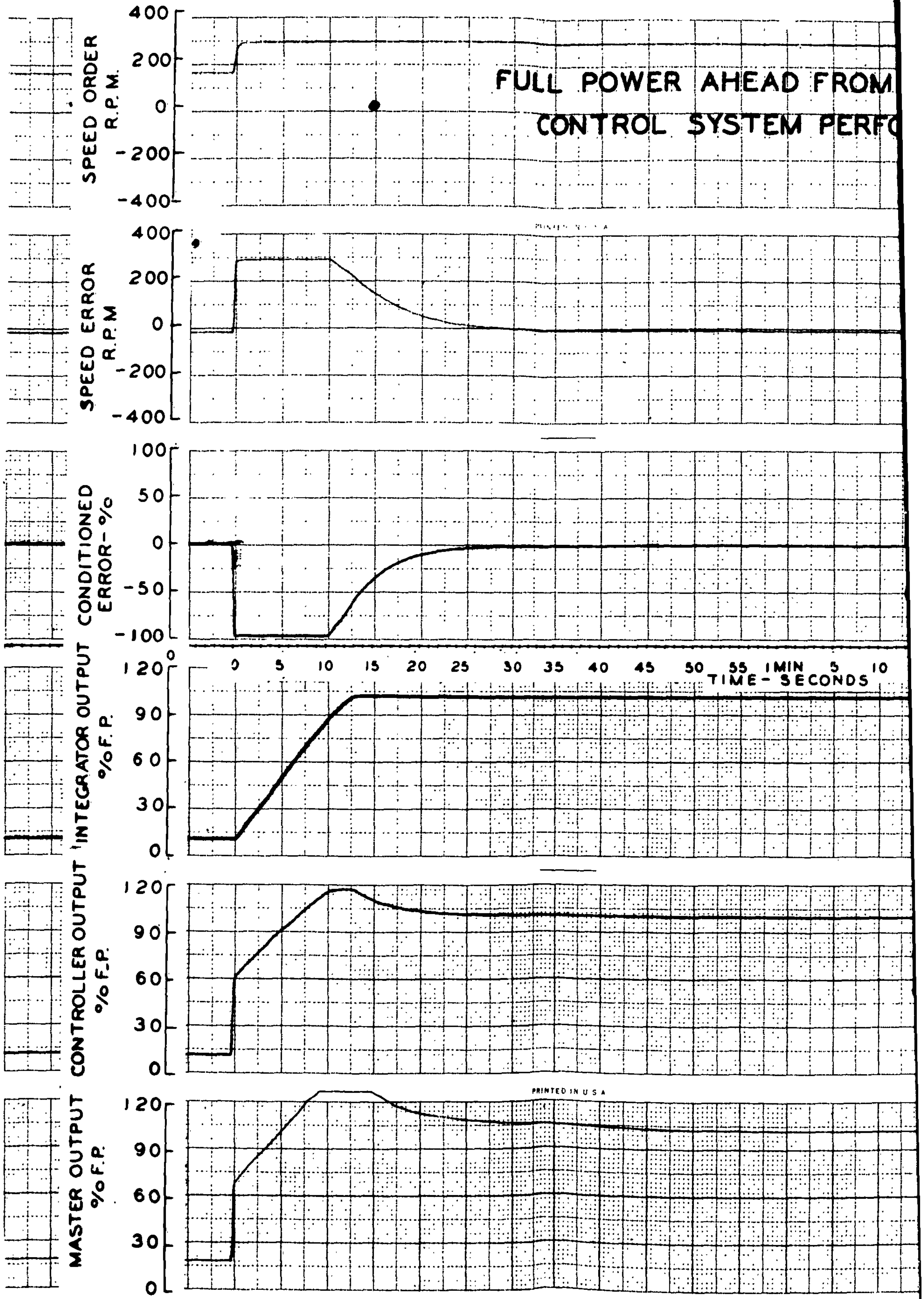

NBTL PROJECT B-311
FULL POWER AHEAD FROM 20 KNOTS
BOILER PERFORMANCE
MASSA
0 5 10 15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
2
MASSA

FIG. 24 B


FULL POWER AHEAD FROM
CONTROL SYSTEM PERF
SPEED ORDER R.P.M.
SPEED ERROR R.P.M.
CONDITIONED ERROR-%
INTEGRATOR OUTPUT % F.P.
CONTROLLER OUTPUT % F.P.
MASTER OUTPUT % F.P.
TIME-SECONDS
1 MIN
PRINTED IN U.S.A.

1

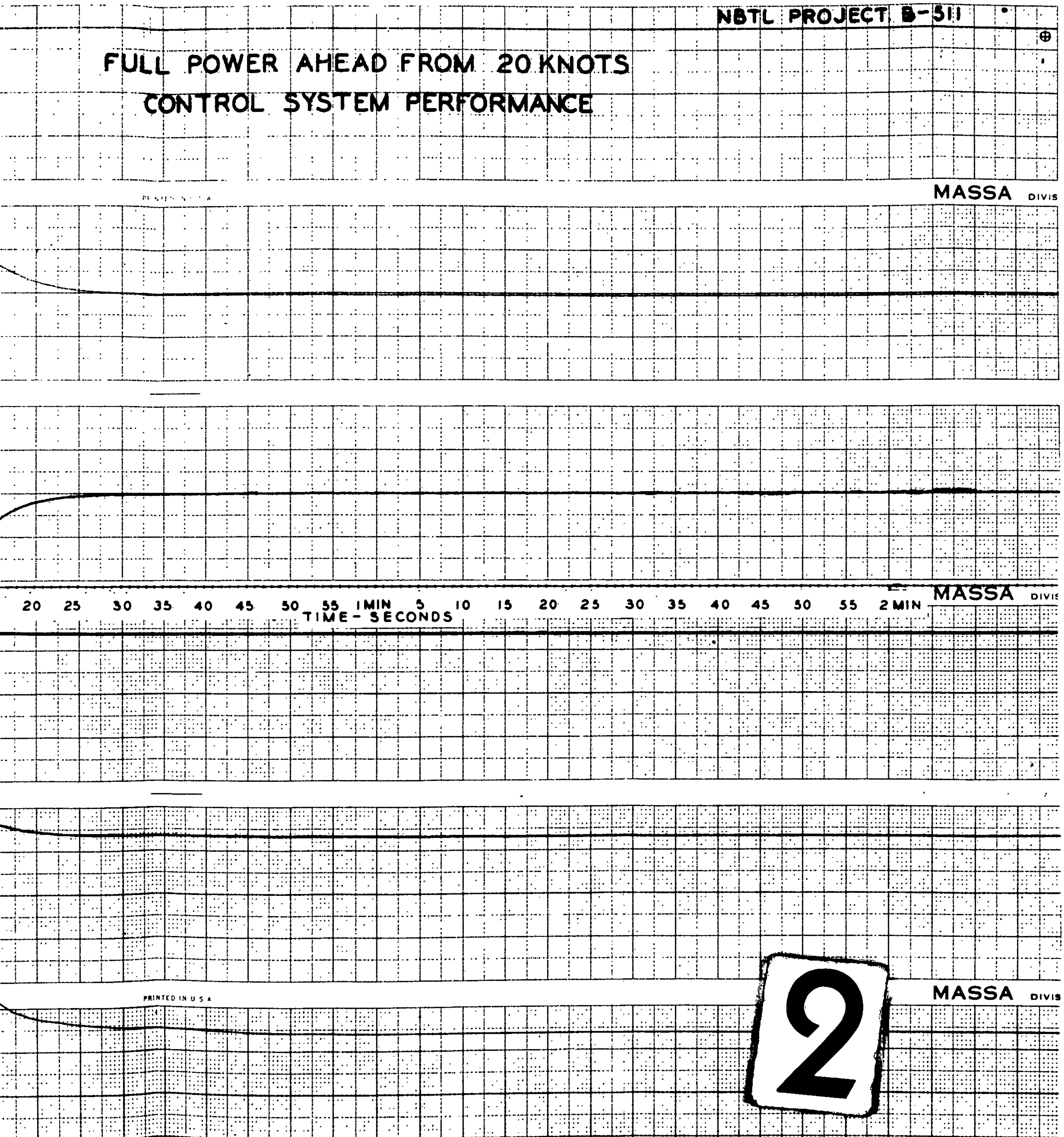
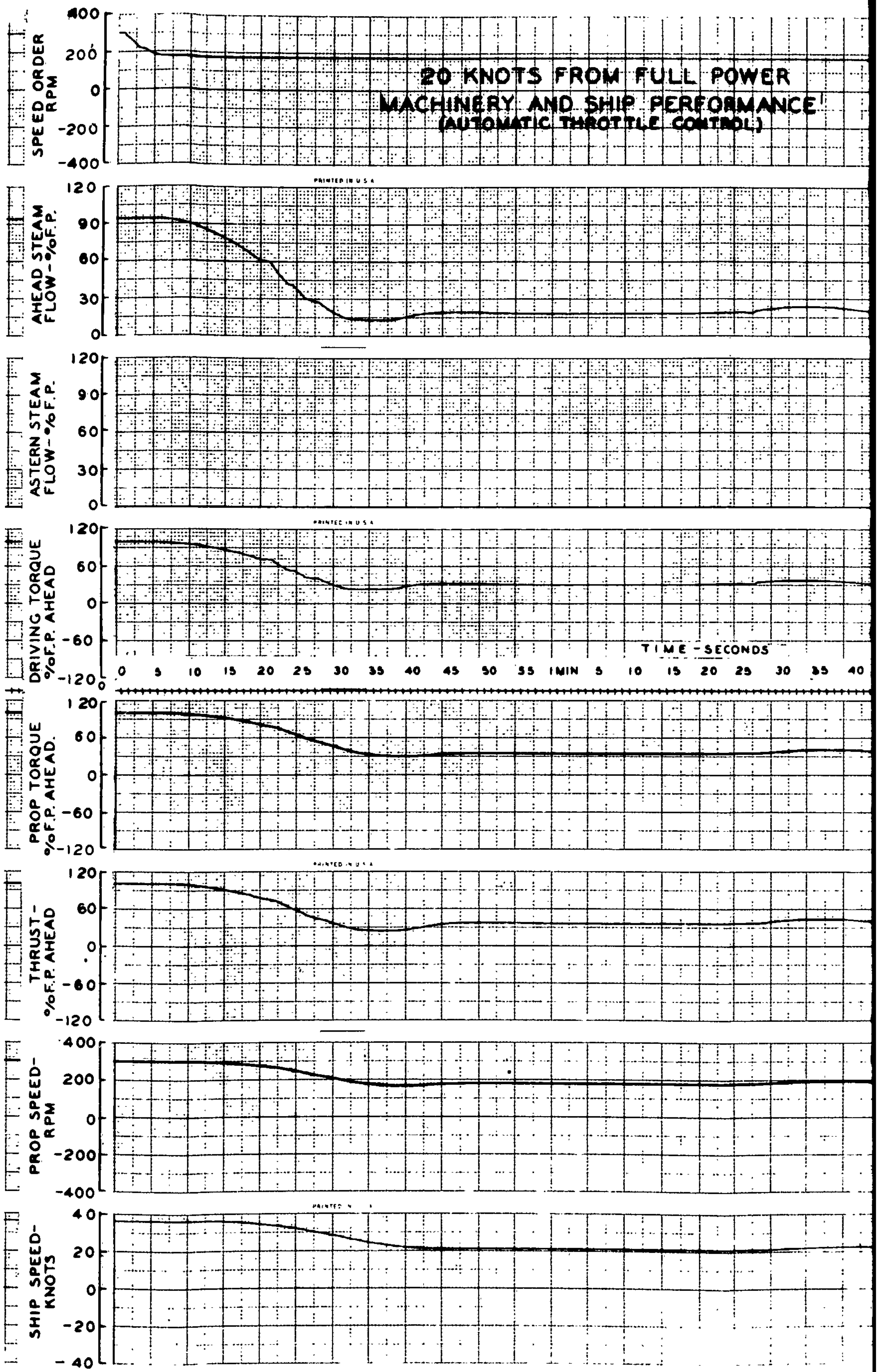
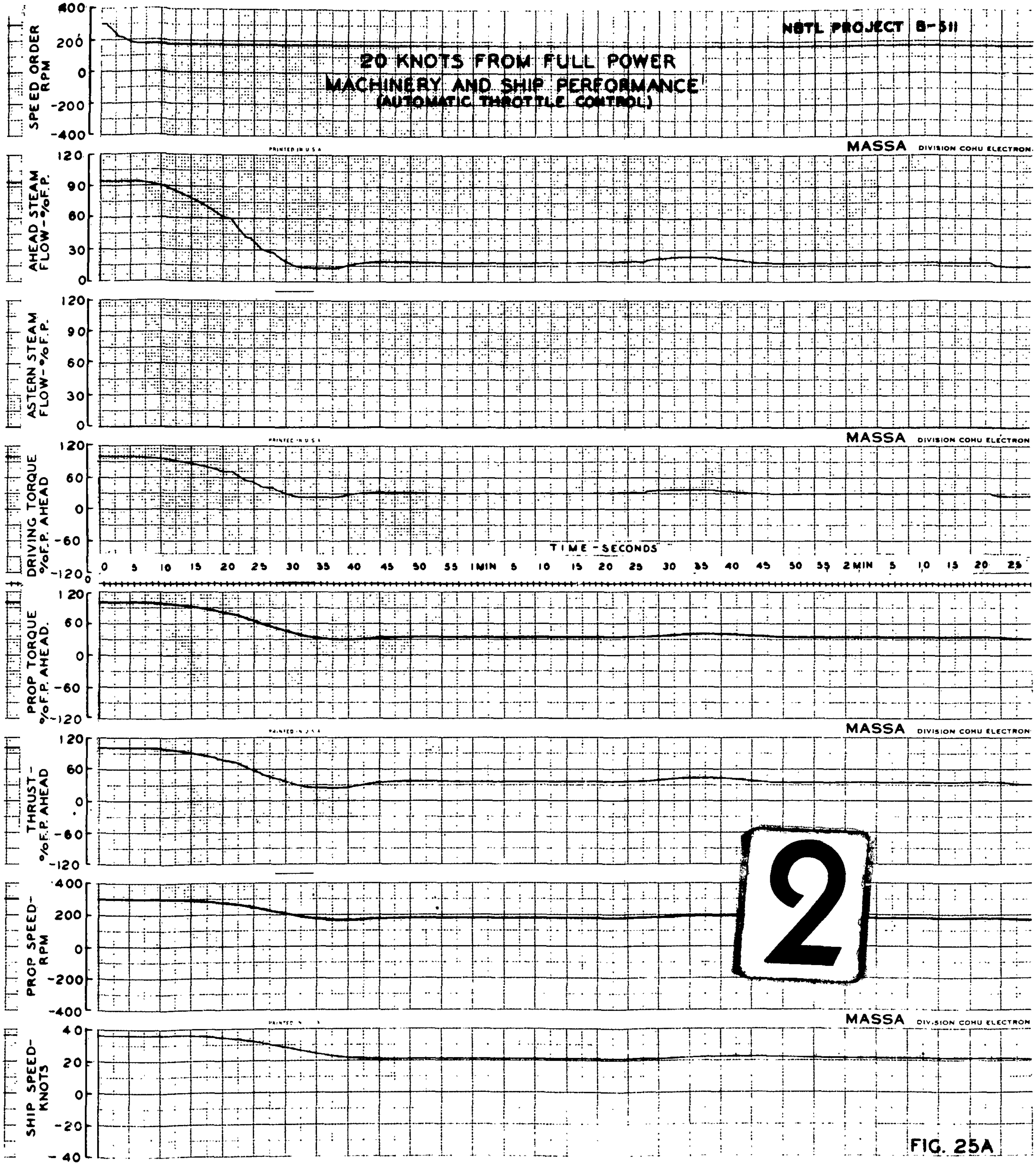
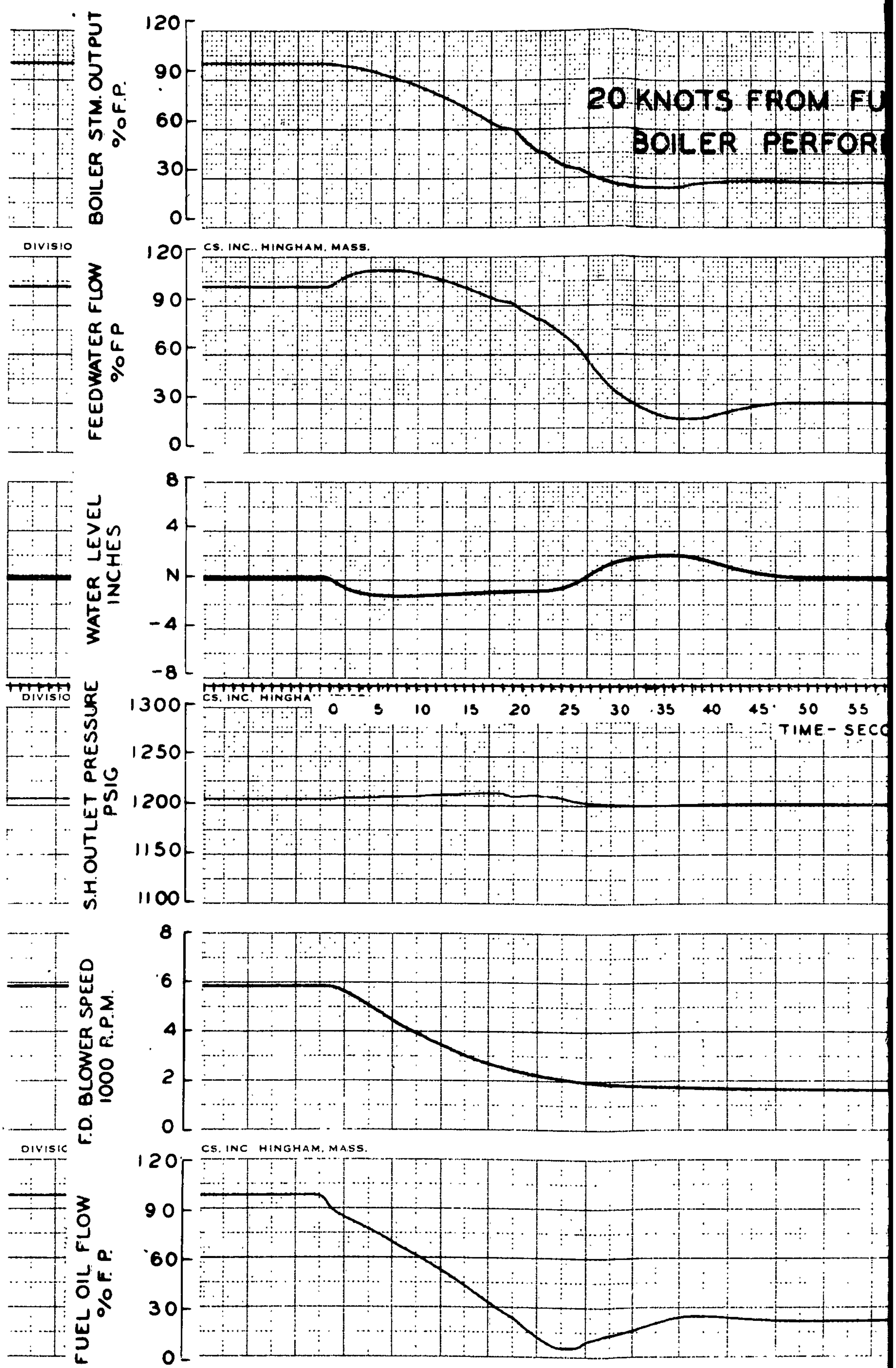

NBTL PROJECT B-511
FULL POWER AHEAD FROM 20 KNOTS
CONTROL SYSTEM PERFORMANCE
MASSA DIVIS
20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
MASSA DIVIS
PRINTED IN U.S.A.
MASSA DIVIS
2

FIG. 24C


20 KNOTS FROM FULL POWER
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
SPEED ORDER RPM
400
200
0
-200
-400
AHEAD STEAM FLOW-%F.P.
120
90
60
30
0
ASTERN STEAM FLOW-%F.P.
120
90
60
30
0
DRIVING TORQUE %F.P. AHEAD
120
60
0
-60
-120
TIME-SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20 25 30 35 40
PROP TORQUE %F.P. AHEAD.
120
60
0
-60
-120
THRUST-%F.P. AHEAD
120
60
0
-60
-120
PROP SPEED-RPM
400
200
0
-200
-400
SHIP SPEED-KNOTS
40
20
0
-20
-40

1


NBTL PROJECT B-511
20 KNOTS FROM FULL POWER
MACHINERY AND SHIP PERFORMANCE
(AUTOMATIC THROTTLE CONTROL)
SPEED ORDER RPM
AHEAD STEAM FLOW-%F.P.
ASTERN STEAM FLOW-%F.P.
DRIVING TORQUE %F.P. AHEAD
TIME-SECONDS
PROP TORQUE %F.P. AHEAD.
THRUST-%F.P. AHEAD
PROP SPEED-RPM
SHIP SPEED-KNOTS
MASSA DIVISION COHU ELECTRON
2
FIG. 25A


20 KNOTS FROM FU
BOILER PERFOR
BOILER STM. OUTPUT %o F.P.
120
90
60
30
0
DIVISIO
CS. INC., HINGHAM, MASS.
FEEDWATER FLOW %o F P
120
90
60
30
0
WATER LEVEL INCHES
8
4
N
-4
-8
DIVISIO
CS. INC. HINGHA
0 5 10 15 20 25 30 35 40 45 50 55
TIME- SECO
S.H. OUTLET PRESSURE PSIG
1300
1250
1200
1150
1100
F.D. BLOWER SPEED 1000 R.P.M.
8
6
4
2
0
DIVISIC
CS. INC HINGHAM, MASS.
FUEL OIL FLOW %o F.P.
120
90
60
30
0

1

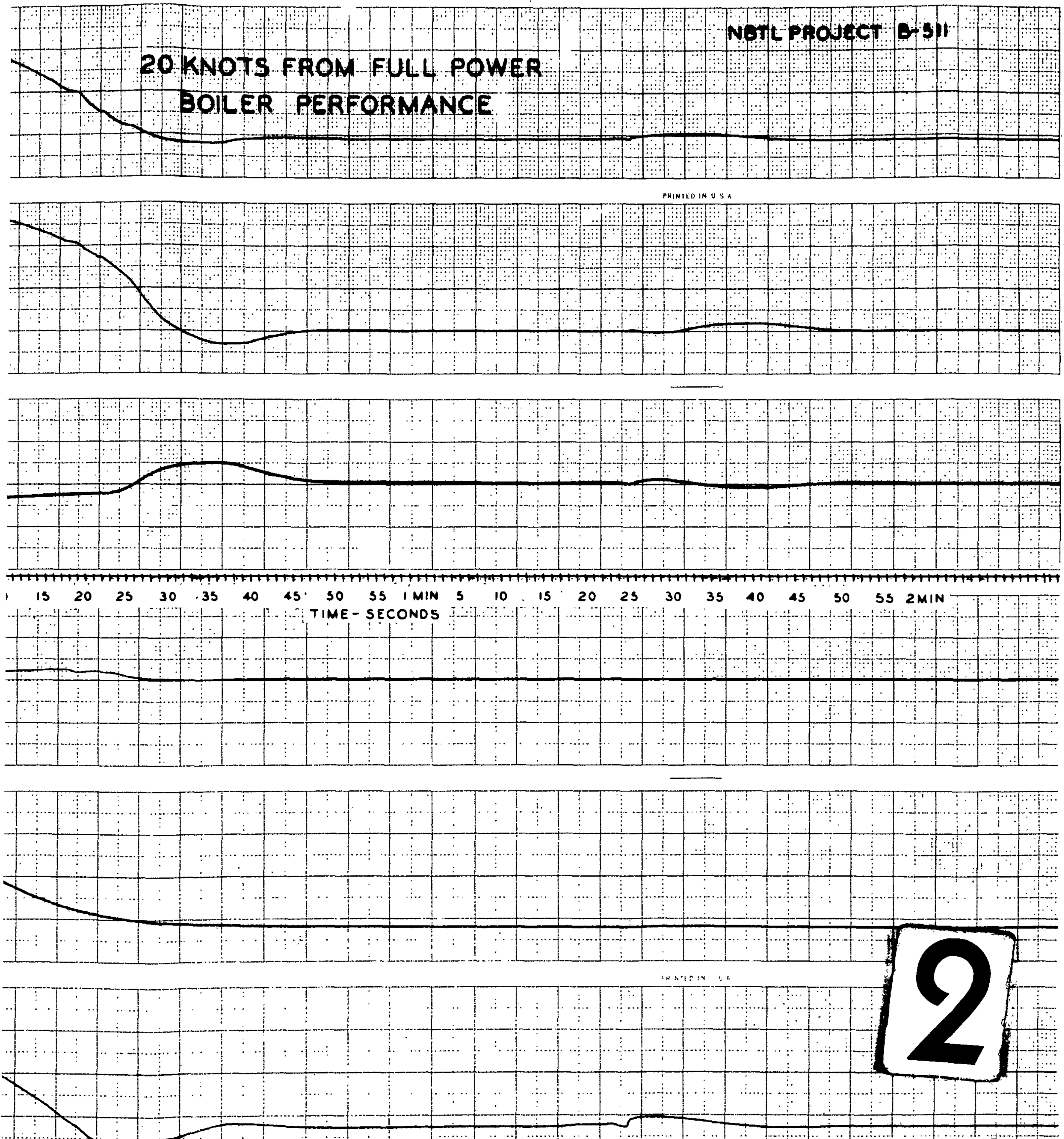
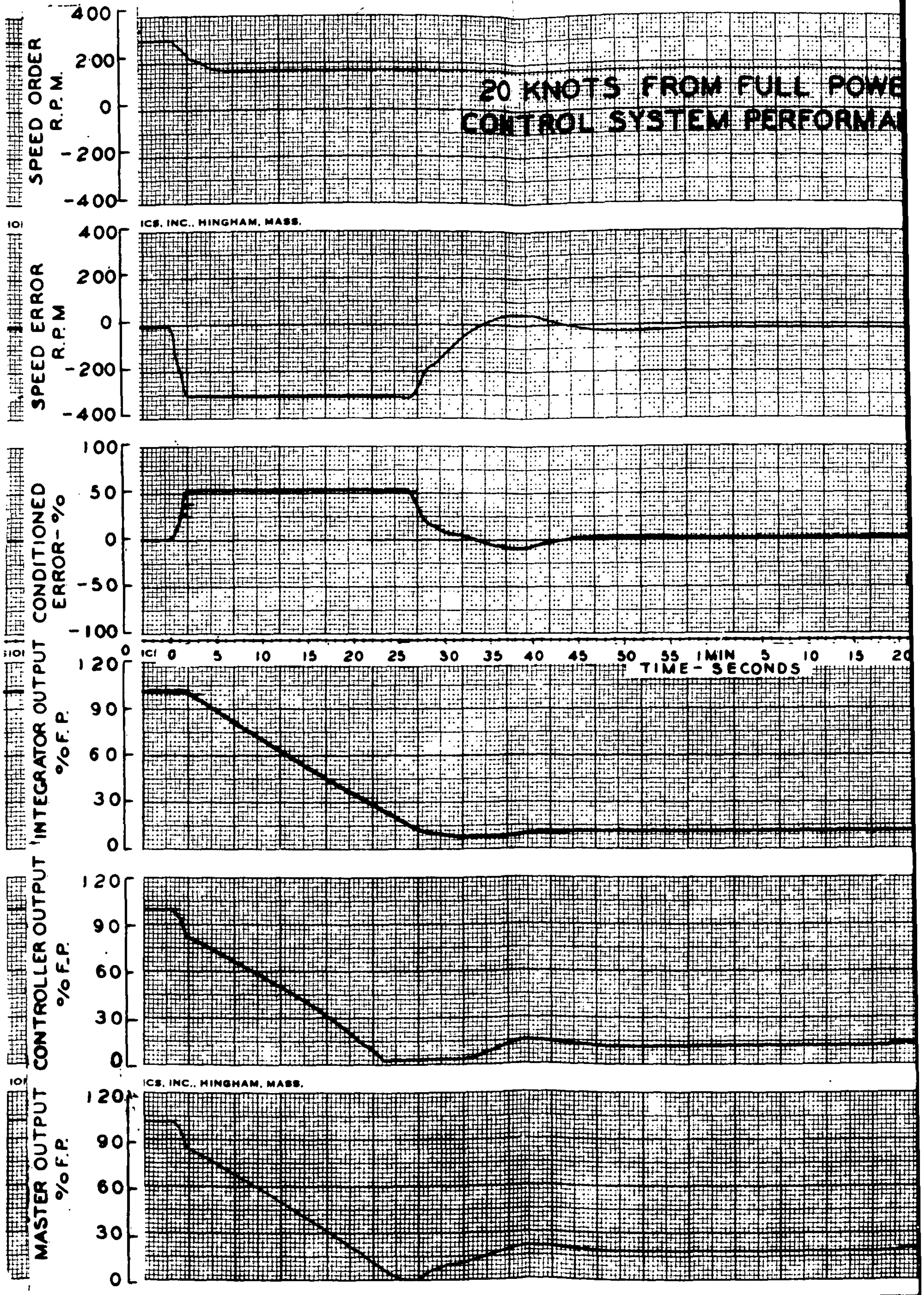

NBTL PROJECT B-511
20 KNOTS FROM FULL POWER
BOILER PERFORMANCE
PRINTED IN U.S.A.
15 20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
2

FIG. 25B



20 KNOTS FROM FULL POWE
CONTROL SYSTEM PERFORMA
SPEED ORDER R.P.M.
400
200
0
-200
-400
ICS, INC., HINGHAM, MASS.
SPEED ERROR R.P.M
400
200
0
-200
-400
CONDITIONED ERROR-%
100
50
0
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5 10 15 20
TIME-SECONDS
INTEGRATOR OUTPUT %F.P.
120
90
60
30
0
CONTROLLER OUTPUT %F.P.
120
90
60
30
0
ICS, INC., HINGHAM, MASS.
MASTER OUTPUT %F.P.
120
90
60
30
0

1

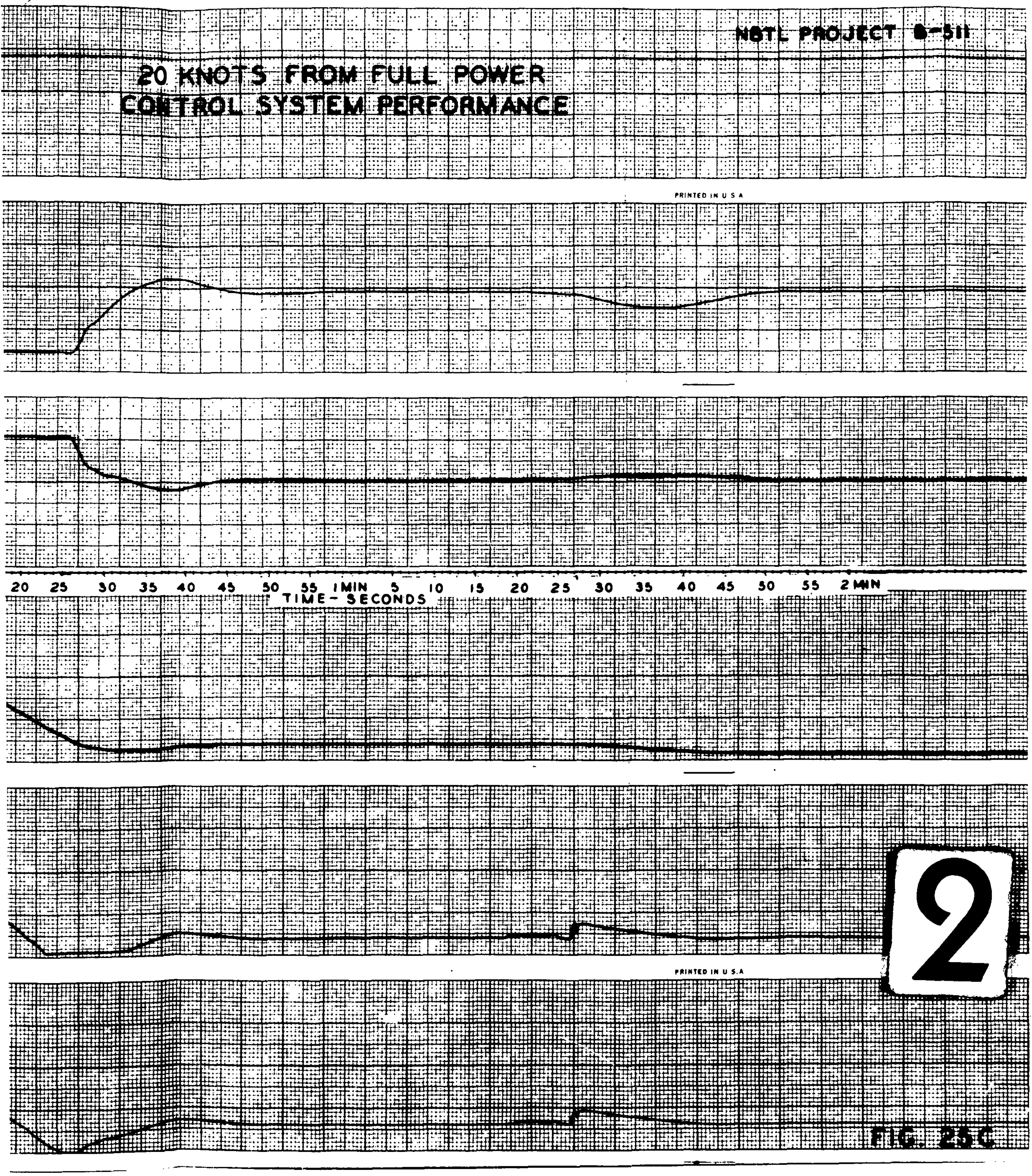
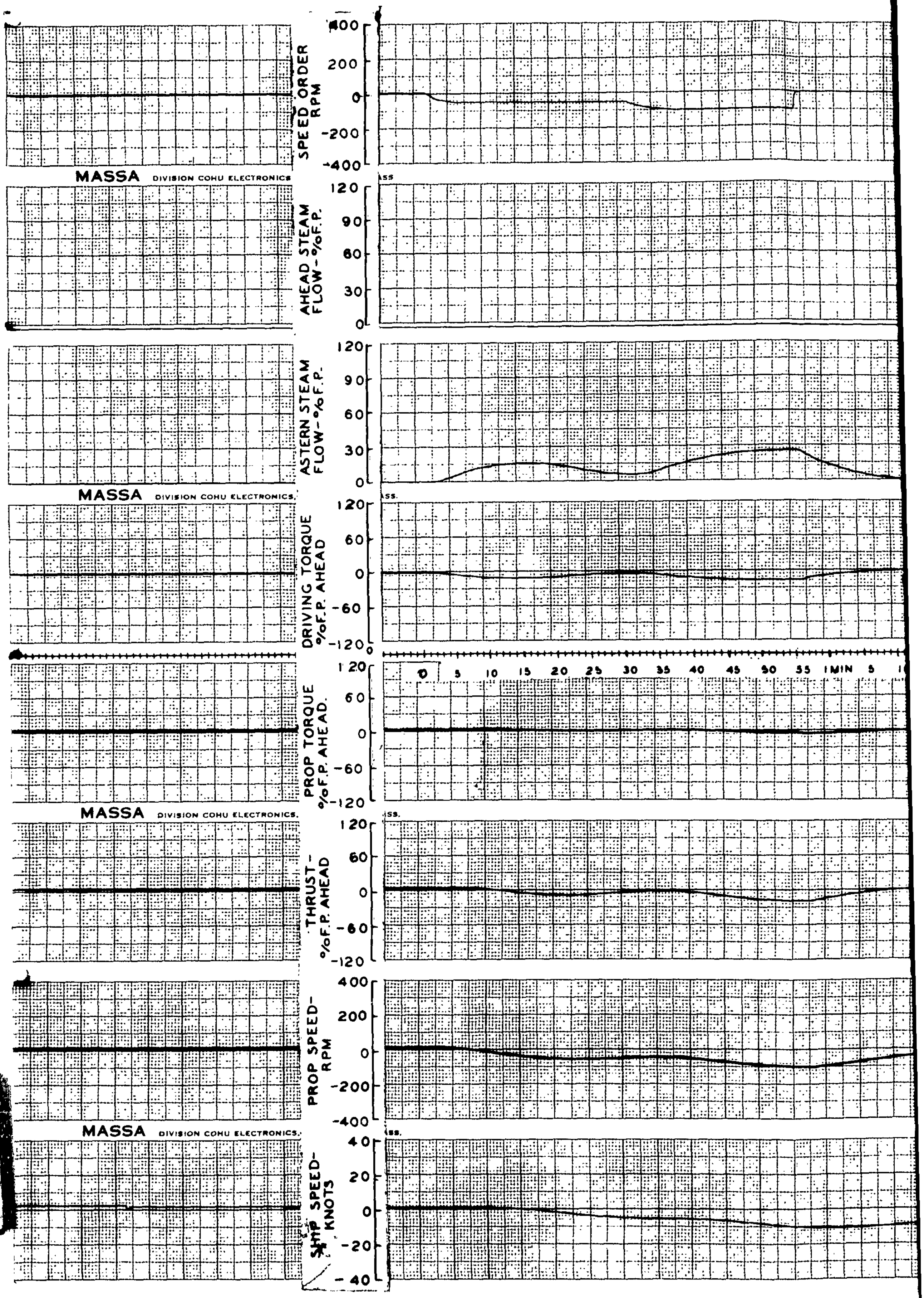
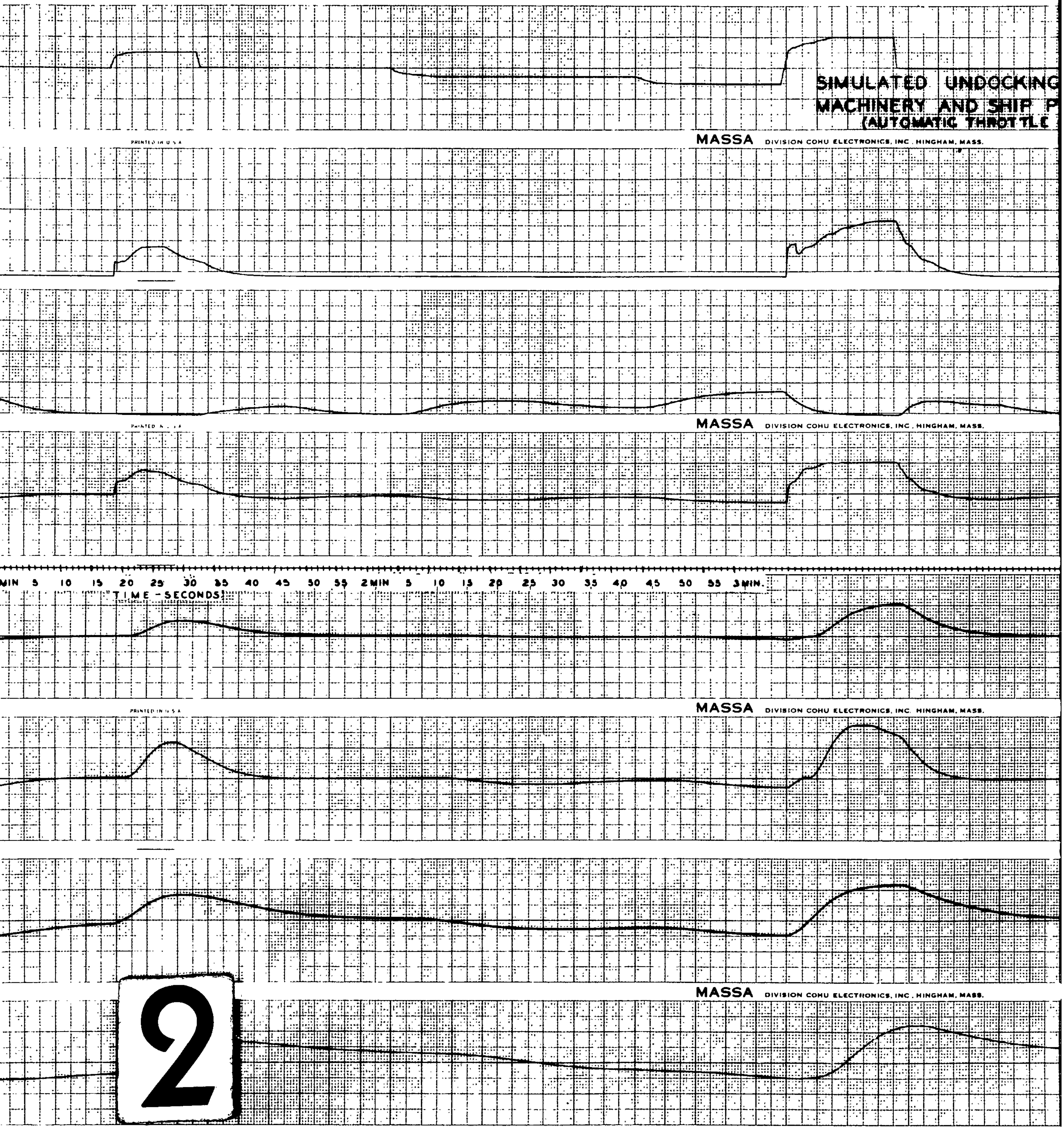

NBTL PROJECT B-511
20 KNOTS FROM FULL POWER
CONTROL SYSTEM PERFORMANCE
PRINTED IN U.S.A.
20 25 30 35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2 MIN
TIME - SECONDS
2
PRINTED IN U.S.A.

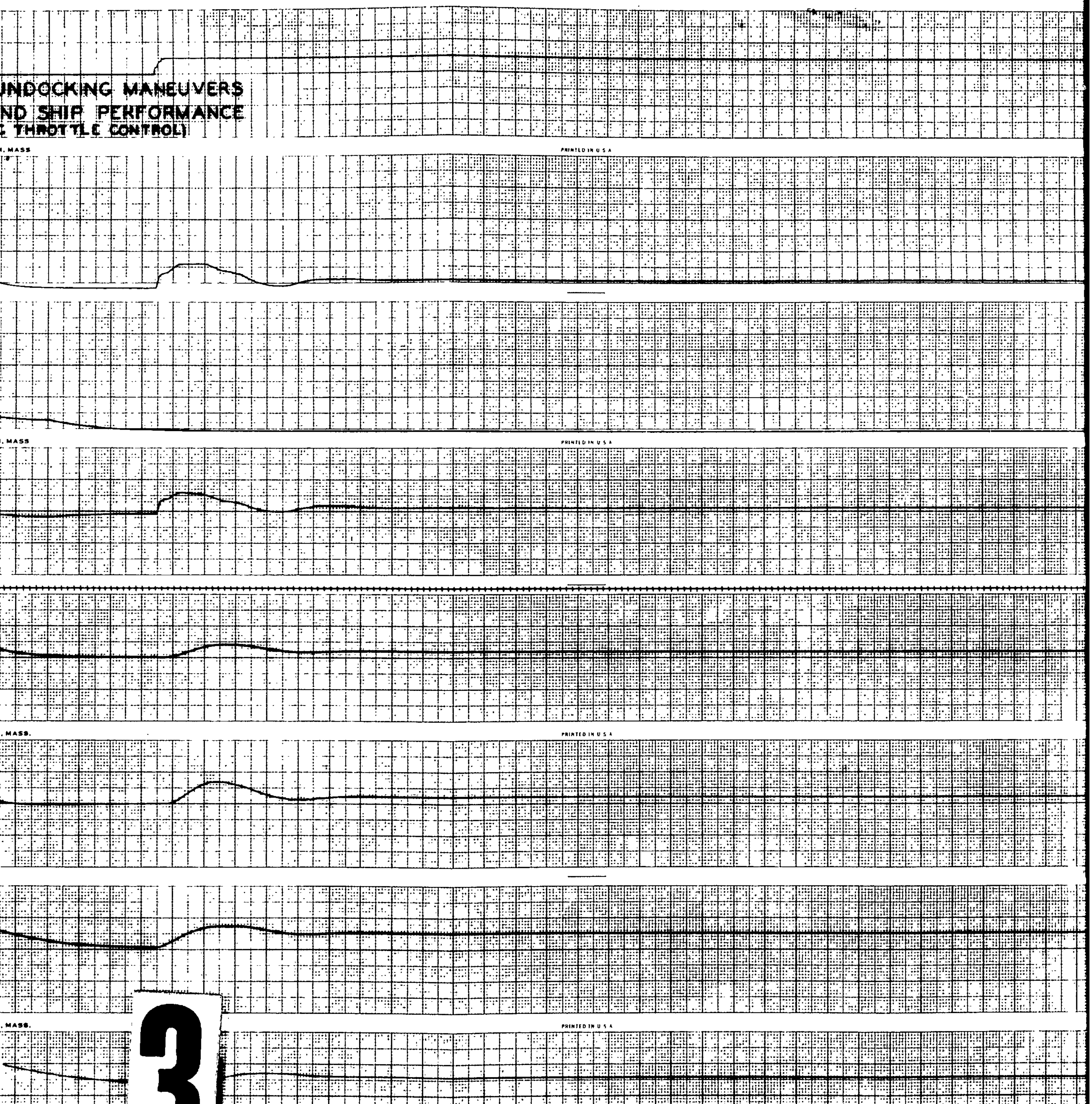
FIG. 25C



SPEED ORDER RPM
400
200
0
-200
-400
MASSA DIVISION COHU ELECTRONICS
AHEAD STEAM FLOW-%F.P.
120
90
60
30
0
ASTERN STEAM FLOW-%F.P.
120
90
60
30
0
MASSA DIVISION COHU ELECTRONICS
DRIVING TORQUE %F.P. AHEAD
120
60
0
-60
-120
0 5 10 15 20 25 30 35 40 45 50 55 1MIN 5
PROP TORQUE %F.P. AHEAD
120
60
0
-60
-120
MASSA DIVISION COHU ELECTRONICS
THRUST-%F.P. AHEAD
120
60
0
-60
-120
PROP SPEED-RPM
400
200
0
-200
-400
MASSA DIVISION COHU ELECTRONICS
SHIP SPEED-KNOTS
40
20
0
-20
-40

1


SIMULATED UNDOCKING
MACHINERY AND SHIP P
(AUTOMATIC THROTTLE
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.
MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN 5 10 15 20 25 30 35 40 45 50 55 3MIN.
TIME - SECONDS
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC. HINGHAM, MASS.
2


UNDOCKING MANEUVERS
ND SHIP PERFORMANCE
THROTTLE CONTROL)
PRINTED IN U S A
3

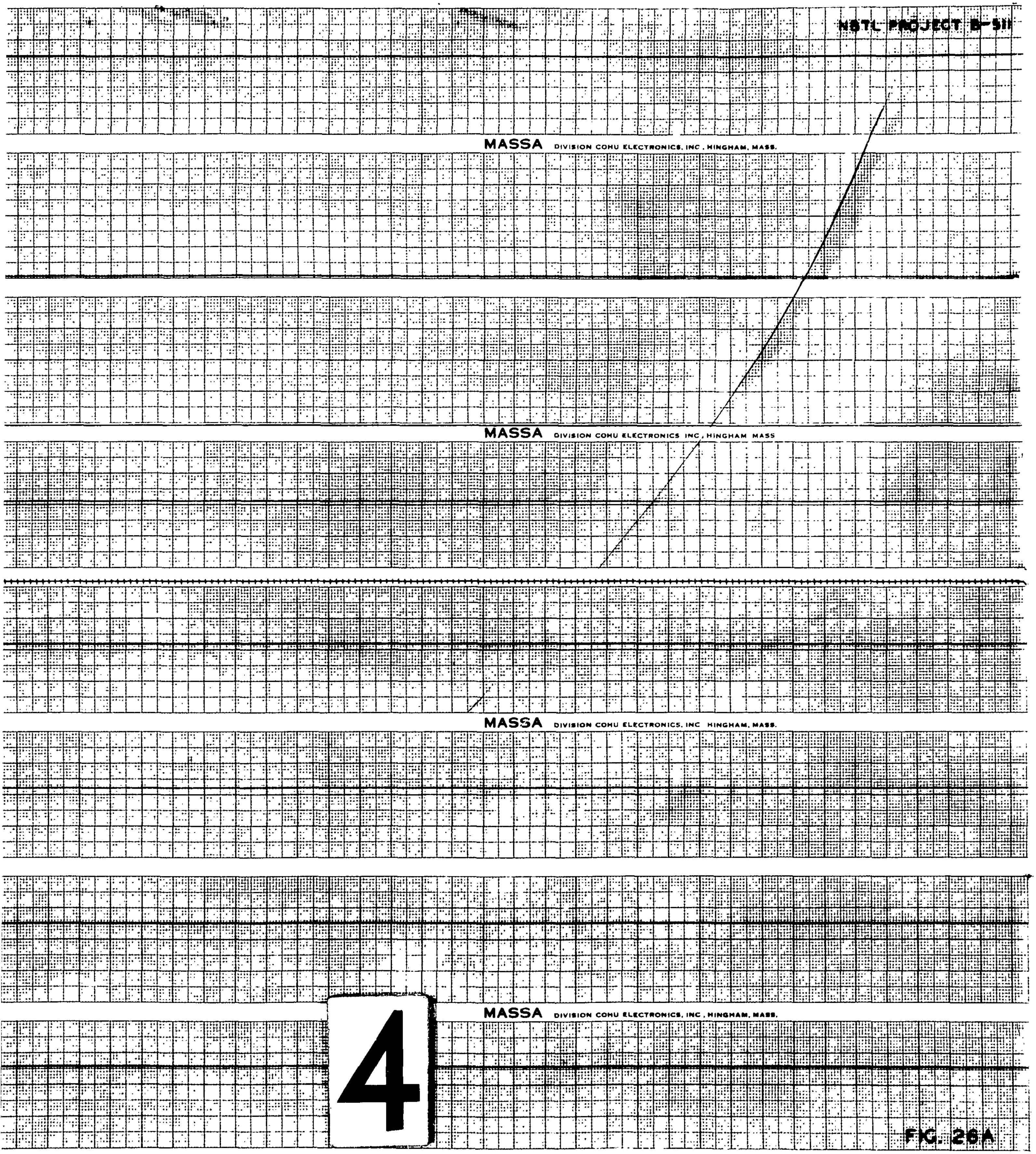
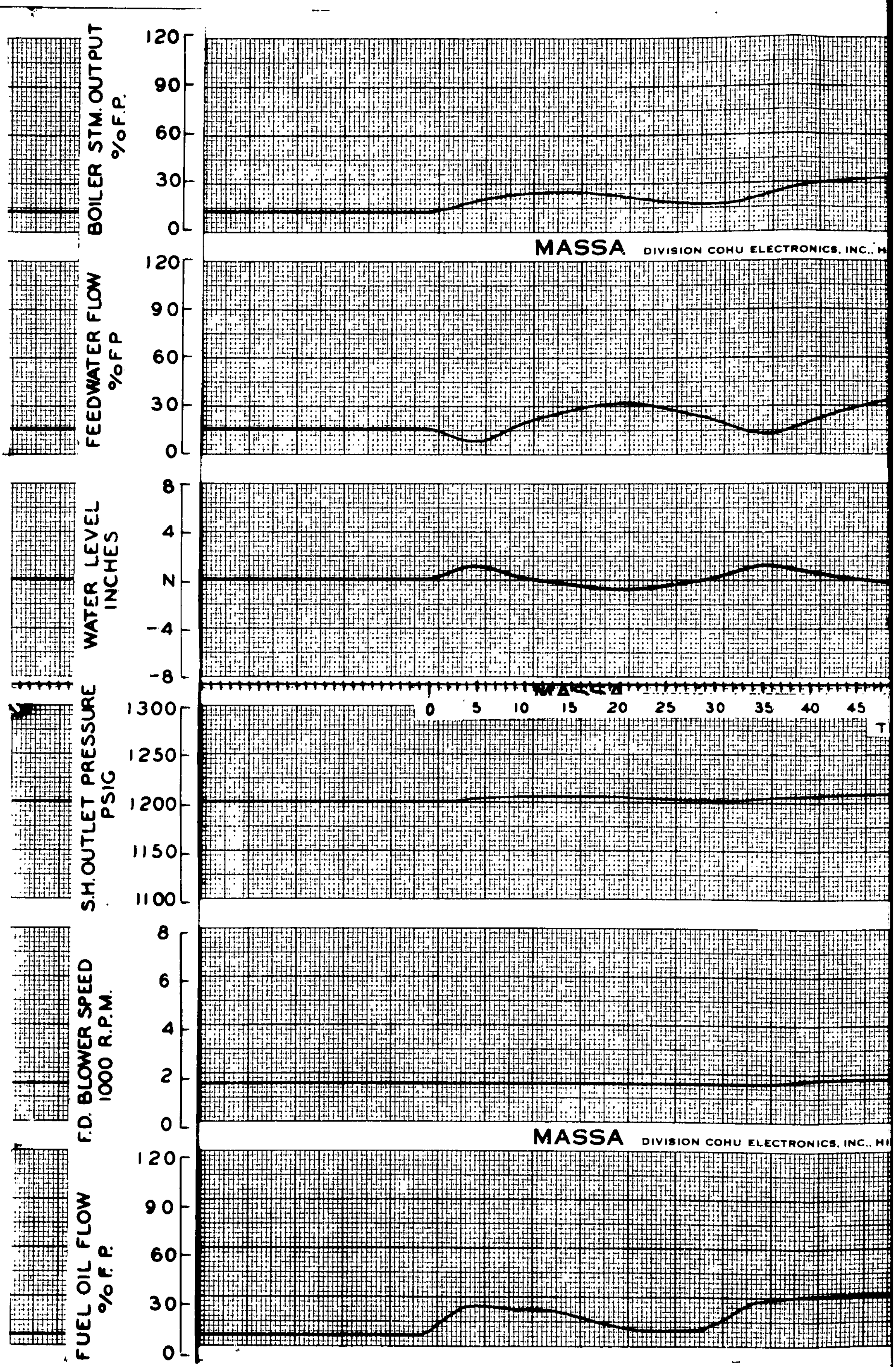
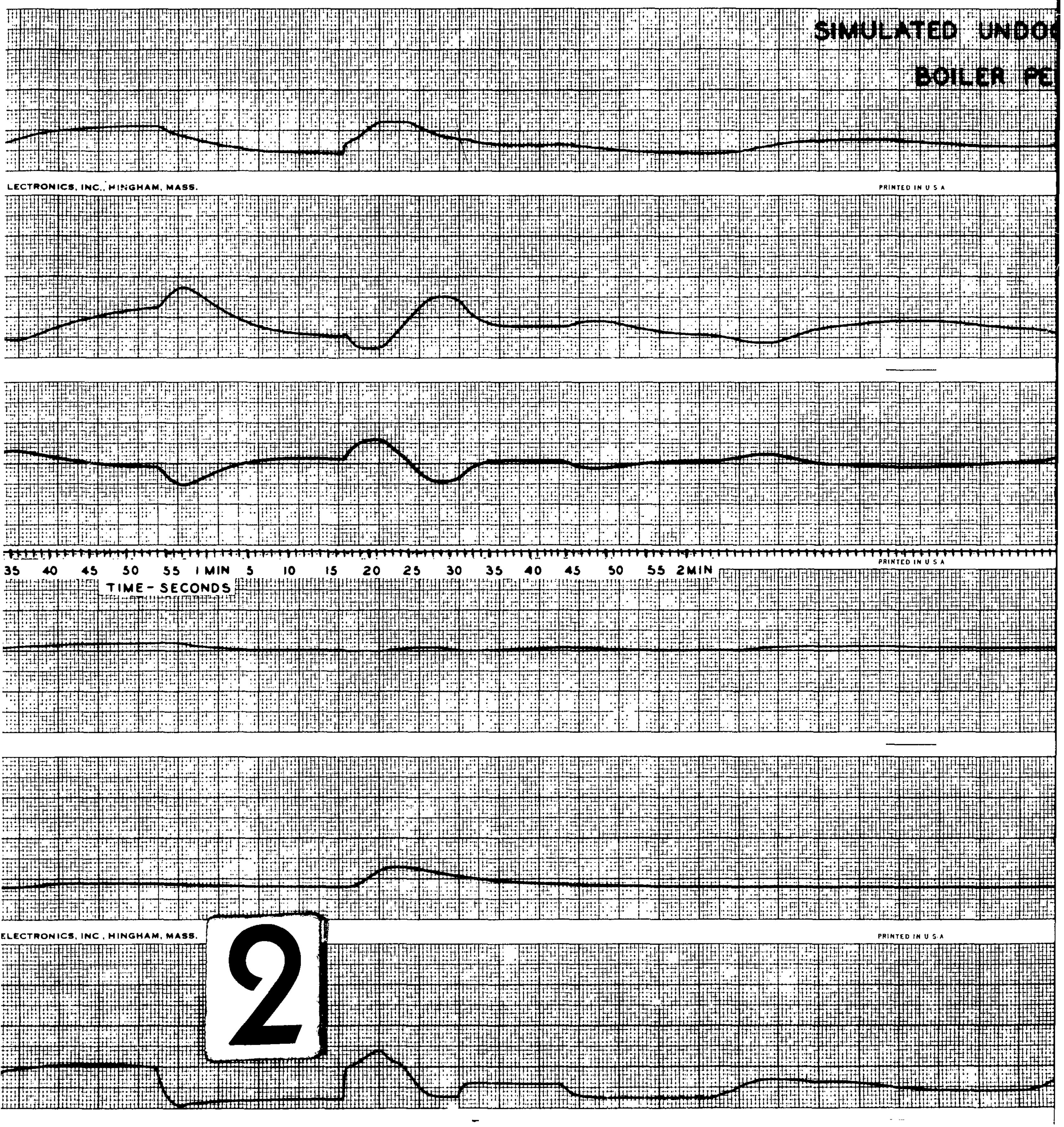
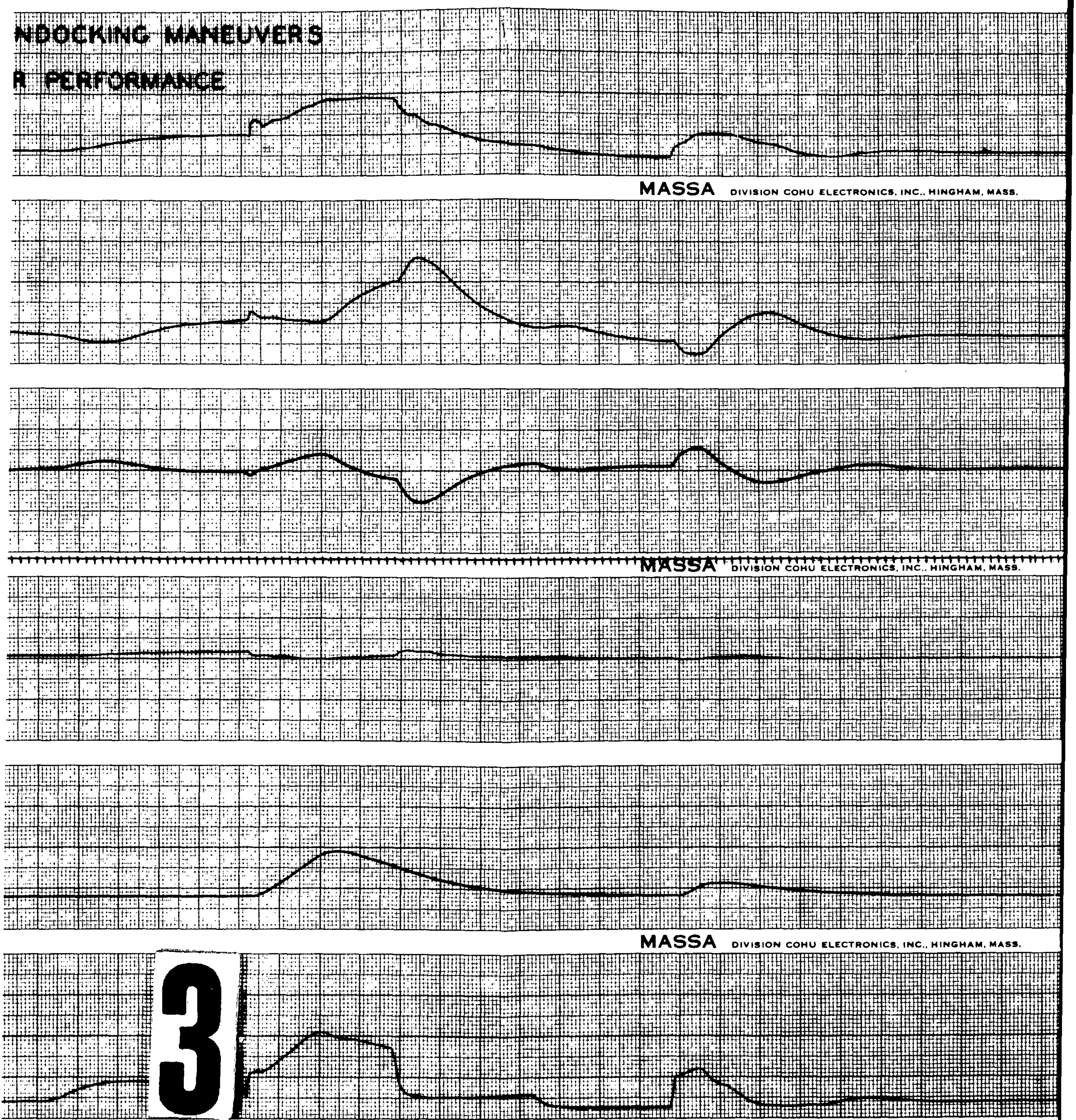

NSTL PROJECT B-511
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
4

FIG. 26A


BOILER STM. OUTPUT %oF.P.
120
90
60
30
0
MASSA DIVISION COHU ELECTRONICS, INC.
FEEDWATER FLOW %oFP
120
90
60
30
0
WATER LEVEL INCHES
8
4
N
-4
-8
S.H. OUTLET PRESSURE PSIG
1300
1250
1200
1150
1100
0
5
10
15
20
25
30
35
40
45
F.D. BLOWER SPEED 1000 R.P.M.
8
6
4
2
0
MASSA DIVISION COHU ELECTRONICS, INC.
FUEL OIL FLOW %o F.P.
120
90
60
30
0

1


SIMULATED UNDO
BOILER PE
LECTRONICS, INC., HINGHAM, MASS.
PRINTED IN U S A
PRINTED IN U S A
35 40 45 50 55 1 MIN 5 10 15 20 25 30 35 40 45 50 55 2MIN
TIME - SECONDS
ELECTRONICS, INC., HINGHAM, MASS.
2
PRINTED IN U S A


NDOCKING MANEUVERS
R PERFORMANCE
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
3

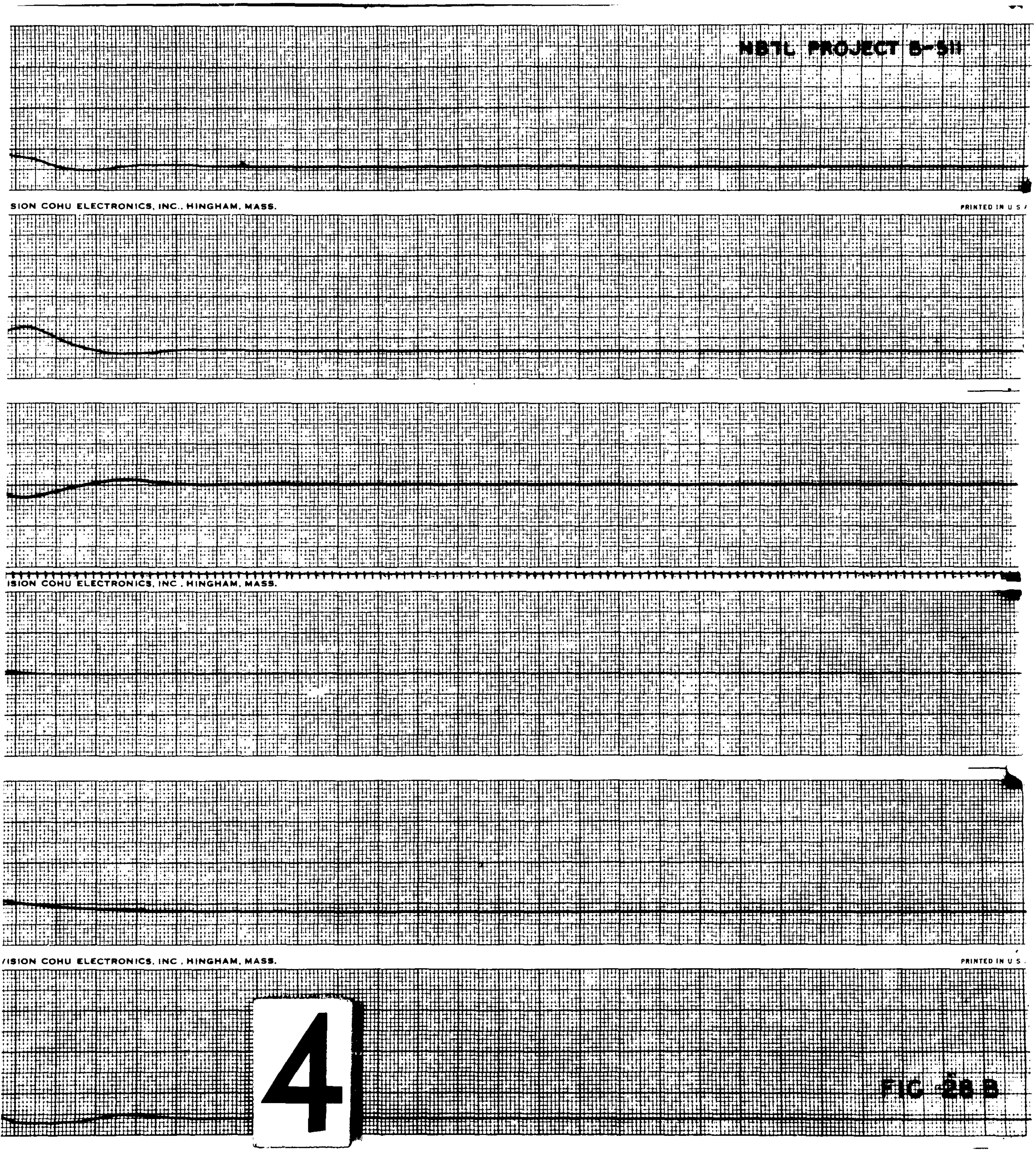
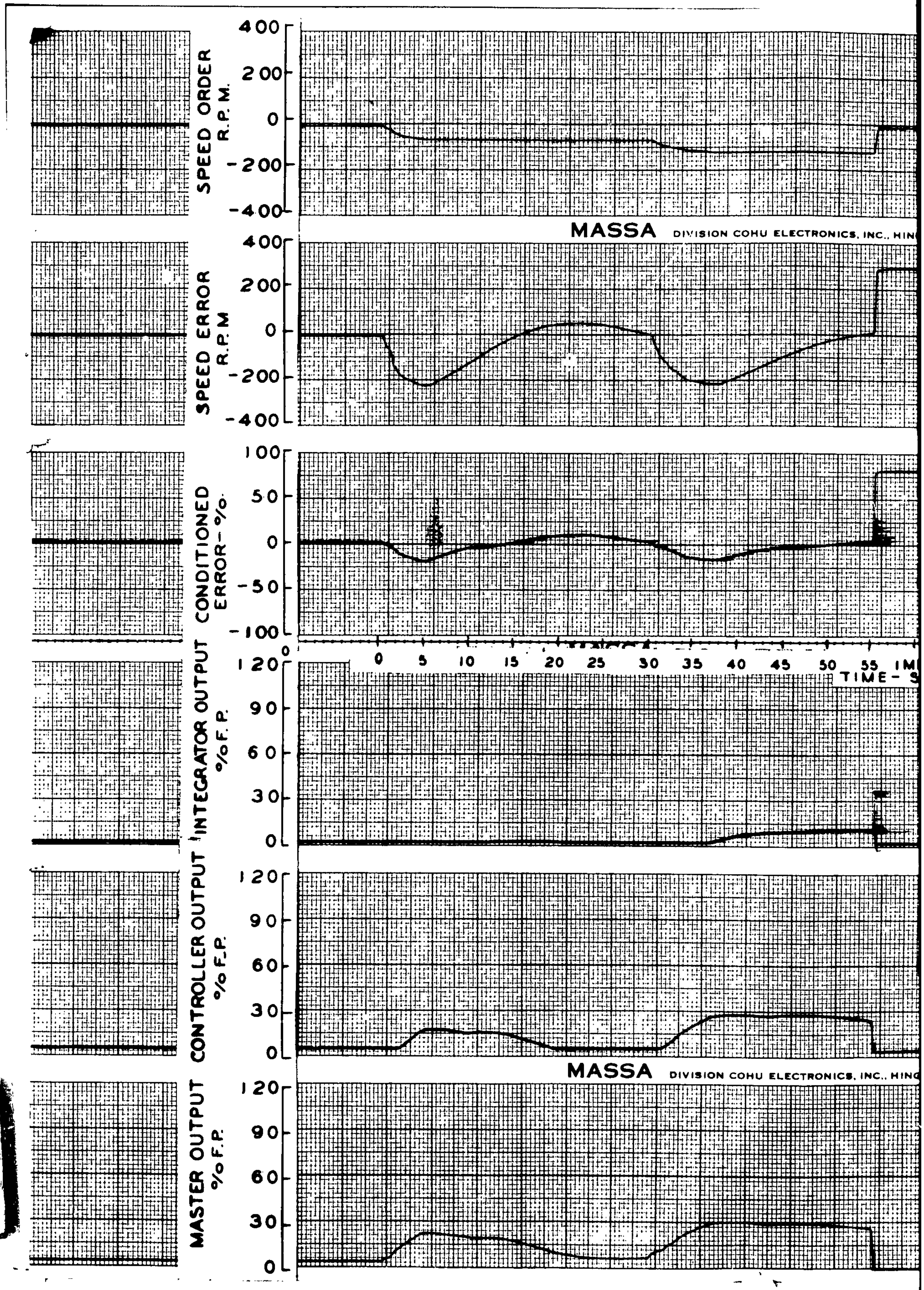
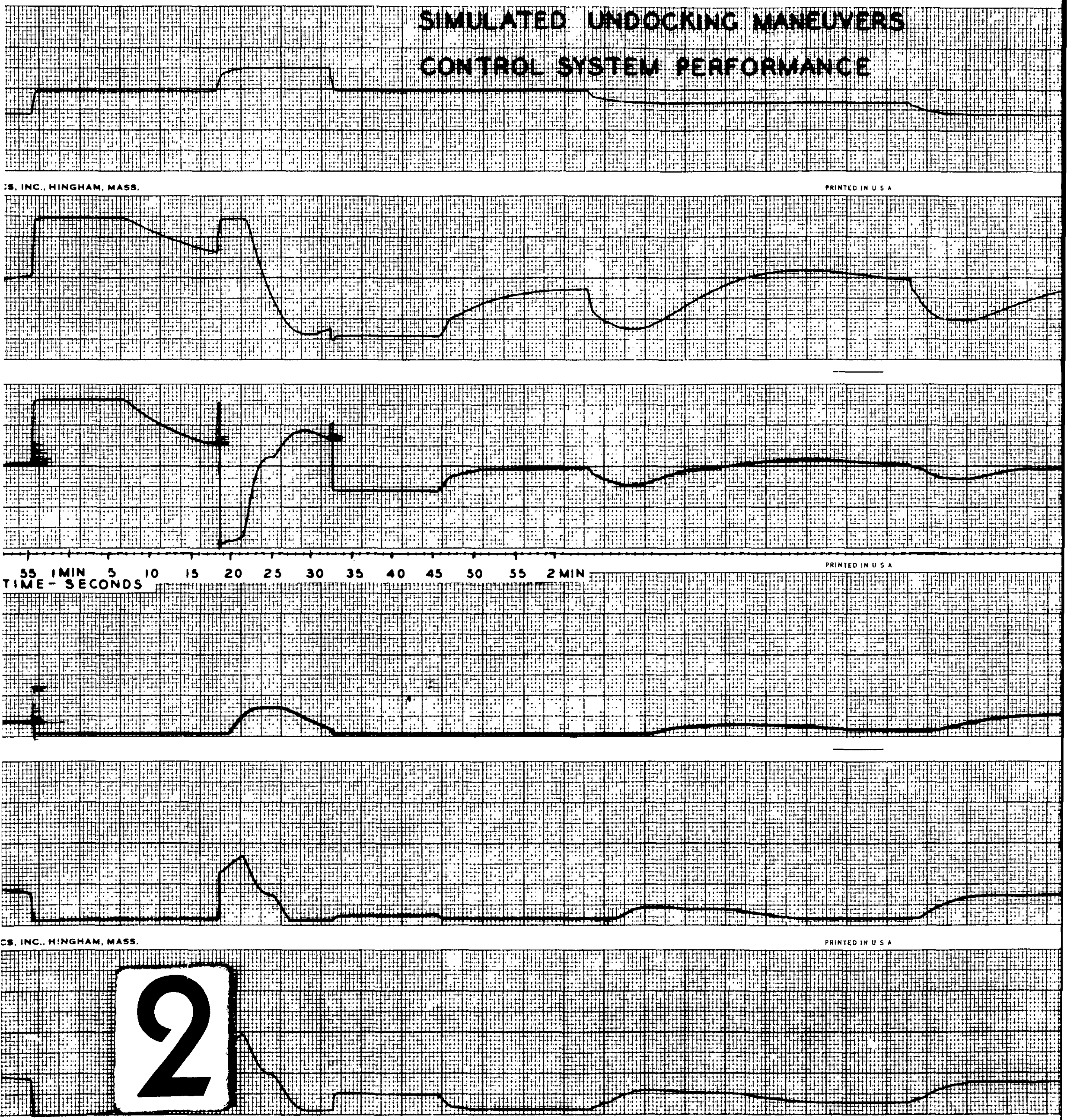

NBTL PROJECT B-511
SION COHU ELECTRONICS, INC., HINGHAM, MASS.
PRINTED IN U S
ISION COHU ELECTRONICS, INC . HINGHAM, MASS.
/ISION COHU ELECTRONICS, INC . HINGHAM, MASS.
PRINTED IN U S
4

FIG 28 B


SPEED ORDER R.P.M.
400
200
0
-200
-400
MASSA DIVISION COHU ELECTRONICS, INC., HIN
SPEED ERROR R.P.M
CONDITIONED ERROR-%
100
50
-50
-100
0 5 10 15 20 25 30 35 40 45 50 55
TIME-S
INTEGRATOR OUTPUT %F.P.
120
90
60
30
CONTROLLER OUTPUT %F.P.
MASTER OUTPUT %F.P.

1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CONTROL SYSTEM PERFORMANCE
CS, INC., HINGHAM, MASS.
PRINTED IN U S A
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TIME - SECONDS
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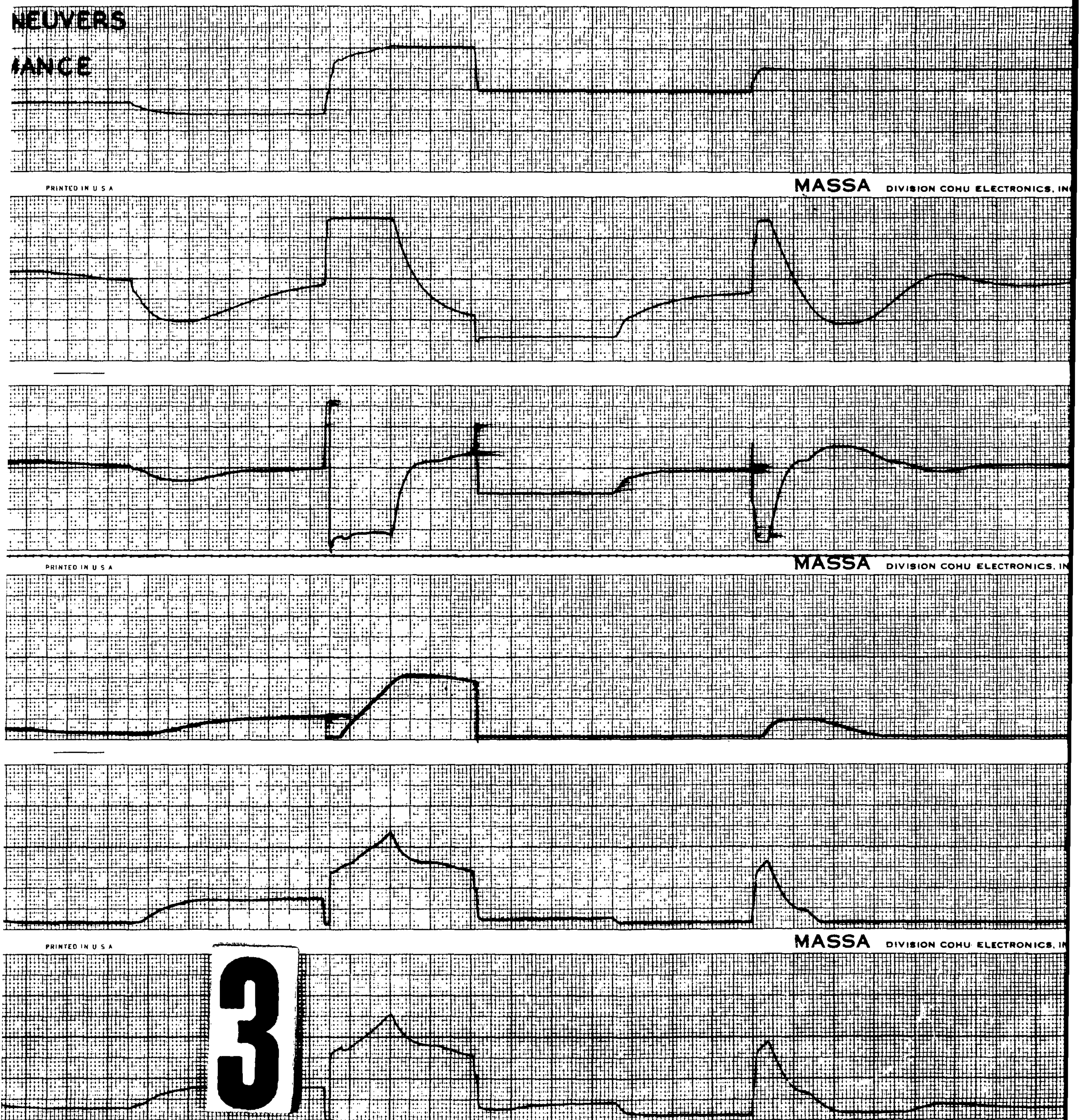
2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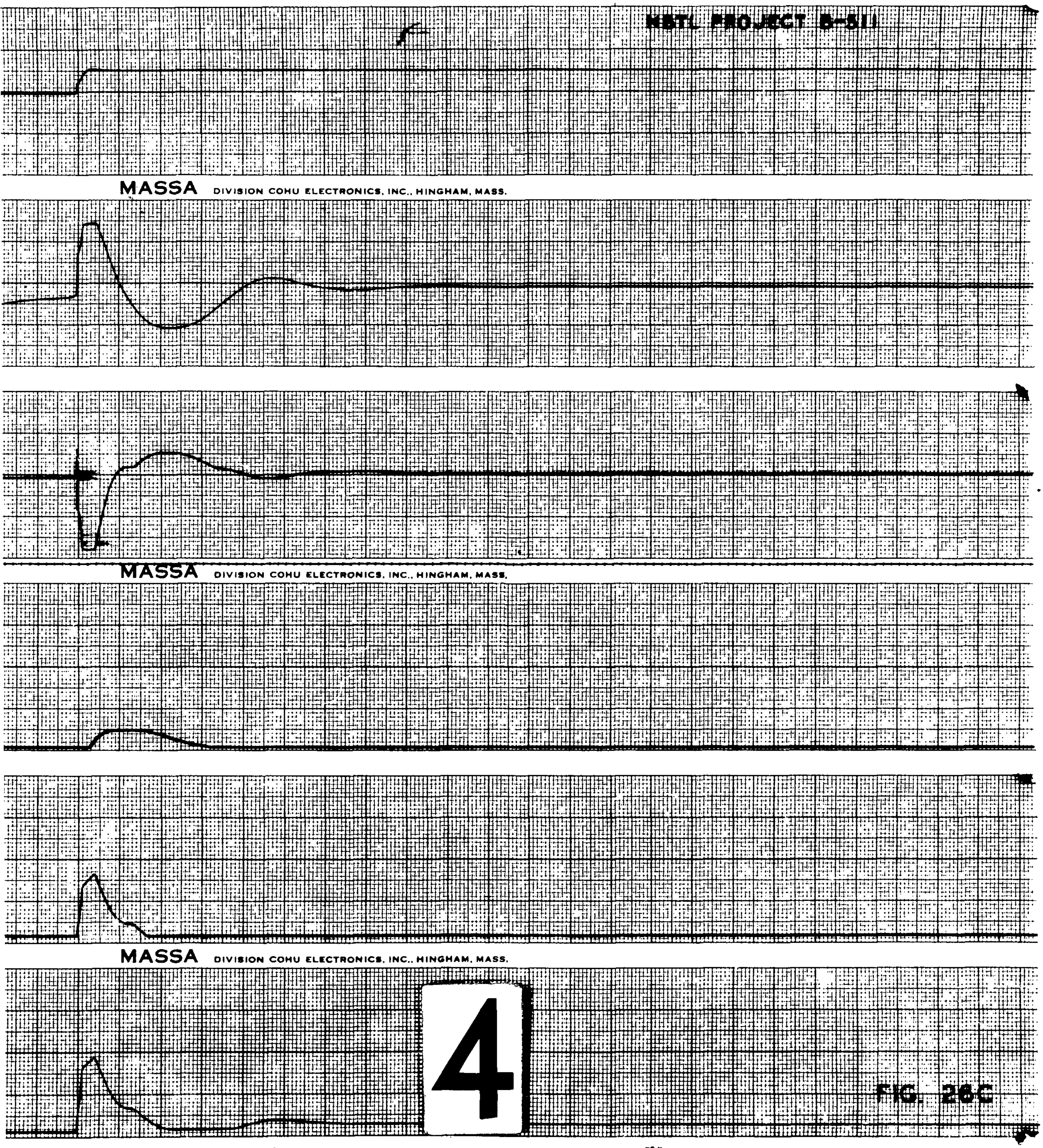
NBTL PROJECT B-511
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
MASSA DIVISION COHU ELECTRONICS, INC., HINGHAM, MASS.
4

FIG. 26C

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Test Report No. B-511-I
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10 June 1963 58 p., 20 illus.
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I. J.W.Banham, Jr. Supervisory Marine Engineer

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The results of simulation studies indicated that the integrated system proposal is technically feasible, and that the system required to produce optimum response and stability is necessarily non-linear and complex

(see other card)

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(see other card)

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